

Neural signatures of predictive strategies track individuals along the autism-schizophrenia continuum

Questa è la versione sottoposta a revisione paritaria (postprint) della seguente opera:

Original

Neural signatures of predictive strategies track individuals along the autism-schizophrenia continuum / Tarasi, Luca; Martelli, Maria Eugenia; Bortoletto, Marta; Di Pellegrino, Giuseppe; Romei, Vincenzo. - In: SCHIZOPHRENIA BULLETIN. - ISSN 0586-7614. - 49:5(2023), pp. 1294-1304. [10.1093/schbul/sbad105]

Availability:

This version is available at: 20.500.11771/41162

Publisher:

Oxford University Press

Published

DOI:10.1093/schbul/sbad105

Terms of use:

This publication is made accessible in accordance with the terms for deposit in the institutional repository, as defined by the IMT School for Advanced Studies Lucca's Open Access Policy. (https://library.imtlucca.it/sites/default/files/regolamento-policy-open-access-imtlib_0.pdf).

Si prega di consultare le pagine informative dell'editore relative alle politiche di autoarchiviazione.

(Article begins on next page)

Neural signatures of predictive strategies track individuals along the autism-schizophrenia continuum

Luca Tarasi^a, Maria Eugenia Martelli^a, Marta Bortoletto^b, Giuseppe di Pellegrino^a, Vincenzo Romei^{a,c}

- a. Centro Studi e Ricerche in Neuroscienze Cognitive, Dipartimento di Psicologia, Alma Mater Studiorum – Università di Bologna, Campus di Cesena, via Rasi e Spinelli, 176, 47521 Cesena, Italy
- b. Laboratorio di Neurofisiologia, IRCCS Istituto Centro San Giovanni di Dio Fatebenefratelli, via pilastri, 4, 25125 Brescia, Italy
- c. Facultad de Lenguas y Educación, Universidad Antonio de Nebrija, Madrid, 28015, Spain

Corresponding Author:

Vincenzo Romei,

Centro Studi e Ricerche in Neuroscienze Cognitive,

Dipartimento di Psicologia, Alma Mater Studiorum – Università di Bologna, Campus di Cesena, via Rasi e Spinelli, 176. 47521 Cesena, Italy.

E-mail: vincenzo.romei@unibo.it

Words count:

Abstract = 250

Text body = 4000

Abstract

Background and Hypothesis

Humans develop a constellation of different representations of the external environment, even in the face of the same sensory exposure. According to the Bayesian framework, these differentiations could be grounded in a different weight assigned to prior knowledge vs. new external inputs in predictive inference. Since recent advances in computational psychiatry suggest that autism (ASD) and schizophrenia (SSD) lie on the two diametric poles of the same predictive continuum, the adoption of a specific inferential style could be routed by dispositional factors related to autistic and schizotypal traits. However, no studies have directly investigated the role of ASD-SSD dimension in shaping the neuro-behavioral markers underlying perceptual inference.

Study Design

We used a probabilistic detection task while simultaneously recording EEG to investigate whether neurobehavioral signatures related to prior processing were diametrically shaped by ASD and SSD traits in the general population (n = 80).

Study Results

We found that the position along the ASD-SSD continuum directed the predictive strategies adopted by the individuals in decision-making. While proximity to the positive schizotypy pole was associated with the adoption of the predictive approach associated to the hyper-weighting of prior knowledge, proximity to ASD pole was related to strategies that favored sensory evidence in decision-making.

Conclusions

These findings revealed that the weight assigned to prior knowledge is a marker of the ASD-SSD continuum, potentially useful for identifying individuals at-risk of developing mental disorders and for understanding the mechanisms contributing to the onset of symptoms observed in ASD and SSD clinical forms.

Keywords: Alpha oscillations, Perceptual decision-making, Predictive coding, Computational psychiatry

Introduction

The Bayesian approach conceptualizes the brain as an inferential organ¹ that optimizes perception by integrating sensory information coming from the outside world with prior knowledge structured through experience. This framework aids in understanding the generative mechanisms underpinning the constellation of predictive styles observable in the general and psychiatric populations, that would derive from a different weight each individual assigns to priors vs. new sensory information^{2,3}. In a recent paper⁴, we shed light on these inter-individual differences by identifying predictive styles marked by the tendency to overweight vs underweight prior information. Using a probabilistic detection task, we induced a perceptual expectation by informing the participants, on a trial-by-trial basis, about the probability of target occurrence. We demonstrated that prior knowledge does not affect objective performance (i.e., sensitivity and drift rate). Instead, it induces a significant shift in response strategy, being more liberal for highly expected target trials and more conservative for low expected target trials. Crucially, we observed significant variations in the magnitude of bias shifting across participants, testifying that there is wide heterogeneity regarding the weight assigned to prior knowledge within the general population. At the neural level, the amplitude of the posterior alpha oscillations (8-14 Hz) allowed us to intercept these inter-individuals' differentiations: participants (*believers*) who exhibited a massive suppression in the amplitude of alpha oscillations in the high- versus low-probability condition showed a concurrent strong bias shift, whereas individuals (*empiricists*) who exhibited a reduced modulation of alpha amplitude showed a dampened criterion shifting. These findings are in the vein of recent studies revealing that alpha desynchronization is associated with decision-making confidence⁵, visual awareness⁶, and bias in reporting target-presence⁷, but is not associated with increased perceptual performance^{8,9}.

However, we did not investigate which factors might drive the adoption of a particular predictive strategy. According to the autism-schizophrenia continuum model⁹, the cognitive-perceptual styles observable in the Autistic Spectrum Disorder (ASD) and in the Schizophrenic Spectrum Disorder (SSD), may represent one of the critical determinants in this process. ASD has been associated to overweighting of external evidence compared to prior knowledge^{10,11}. For example, perception in individuals with high autistic traits is more constrained by the stimulus objectively displayed rather than expectations about its presence¹². Moreover, ASD relies less on anticipatory neural response in multisensory integration tasks¹³ and did not show posterior alpha desynchronization to behaviorally-relevant targets¹⁴. In contrast, in SSD, ill-adaptive perceptual inference would be due to overweighted priors over sensory evidence^{15,16}. Powers et al.¹⁷ identified that, in a visual-auditory conditioning task, the number and confidence of conditioned hallucinations were positively correlated with the severity of hallucinations, and that this inclination relies on the overweighting of priors' information in the perceptual process. A comparable result was obtained in individuals at high clinical risk for psychosis who showed behavioral performance consistent with the presence of hyper-precise priors¹⁸. Moreover, an abnormal modulation of alpha activity has been related to maladjustment expectation in social interaction in schizophrenic patients¹⁹.

Starting from these theoretical and empirical works, we explored whether the position along the ASD-SSD continuum could be associated with the predictive style adopted in a perceptual decision-making task. We hypothesize that the more individuals tend to adopt the believer's predictive style, associated with overweighting of prior knowledge, the more they should fall on the SSD side of the ASD-SSD continuum. In contrast, we assume that adherence to the empiricist style, characterized by behavioral and neural markers associated with the suppression of prior knowledge in perceptual inference, should be promoted by proximity to the ASD pole of the continuum.

Methods

Participants

80 participants (43 female, age range 18-35) completed a visual detection task (Fig.1A) in which prior knowledge was manipulated by inducing expectations of target probability. All participants signed a written informed consent prior to take part in the study, which was approved by the Bioethics Committee of the University of Bologna. Part of the sample (n=66) is drawn from a previously published dataset⁴.

Computational modeling on decision-making process

Both Signal Detection Theory (SDT)²⁰ and Drift Diffusion Model (DDM)²¹ were used to unravel which decision-making parameter was influenced by prior information. The SDT measures d' (sensitivity) and c (criterion) were calculated based on the proportion of hits and false alarms separately for trials preceded by low, high, or medium probability cues (See Table S1). A rm-ANOVA was employed to investigate a cue-related effect on SDT indices. The following DDM parameters were allowed to vary according to conditions: drift rate, distance between decisional bounds, starting point of the accumulation process. Traces of model parameters and their autocorrelation have been inspected to evaluate that the models had properly converged (Fig.S2).

EEG analysis

In order to confirm the central role of alpha oscillations in tracking the voluntary modulation of decision bias, we have replicated the EEG analyses strategy performed in our previous study⁴ with this enlarged sample by 1) conducting a time-frequency analysis on the amplitude difference between high- and low-probability trials and 2) assessing whether the degree of criterion shifting due to prior knowledge was related to pre-stimulus alpha amplitude modulation (Fig.S5). Moreover, building from the previous work, we separated the participants as a function of their prior-based pre-stimulus differentiation in alpha amplitude, to investigate whether large vs. small modulation of alpha could underlie the differences in the predictive style adopted. Specifically, for each individual, the mean alpha (~8 - 14 Hz) amplitude value in the pre-stimulus time (~-400 - 0 ms) was considered and the Δ *alpha amplitude* was computed by taking the difference between the alpha amplitude extracted in low- and high-probability trials. This metric was used to delineate two types of predictive styles: the *believers* (i.e., individuals showing an above-median Δ alpha amplitude) and the *empiricists* (i.e., individuals showing a below-median Δ alpha amplitude). To reconfirm that the two clusters of individuals showed specific differentiation related to bias-shift, we assessed with an independent-samples t-test whether the SDT and DDM indices were differently modulated by the group factor.

Autism-schizophrenic continuum

The autistic traits in our sample were measured using the Autism-Spectrum Quotient test (AQ)²², while schizotypy was assessed using the Schizotypal Personality Questionnaire (SPQ)²³. An independent-samples t-test was employed to

explore which specific subscales of the AQ and SPQ had different magnitude between the group of believers and empiricists (See Supplementary materials). Moreover, in order to identify where individuals on the autism-schizophrenia axis lay, a principal component analysis (PCA, see supplementary materials) was performed on the correlation matrix of the AQ and SPQ subscales. The first two principal components were extracted and the second one (PC2) was selected for subsequent analyses because, according to previous literature²⁴⁻²⁷, it is supposed to capture the diametric relationship between these two conditions. Then, to assess whether the predictive style adopted by the participants could be related to the individual position along the autism-schizophrenia axis, independent-sample t-tests were employed to investigate whether the individual PC2 score showed statistically significant differences between the believers and empiricists group. We checked that the results obtained from the median-split analysis remained valid even when using the continuous variables Δ alpha amplitude and Δ criterion as dependent variables and the PC2 score as a predictor. Finally, a mediation analysis was conducted to probe effects of ASD-SSD continuum factor on Δ criterion, mediated by any effects exerted by it on Δ *alpha amplitude* regulation. All the analyses were carried out with standardized values for all the variables, and we report 95% confidence interval based on 5000 bootstrap iterations (bias-corrected).

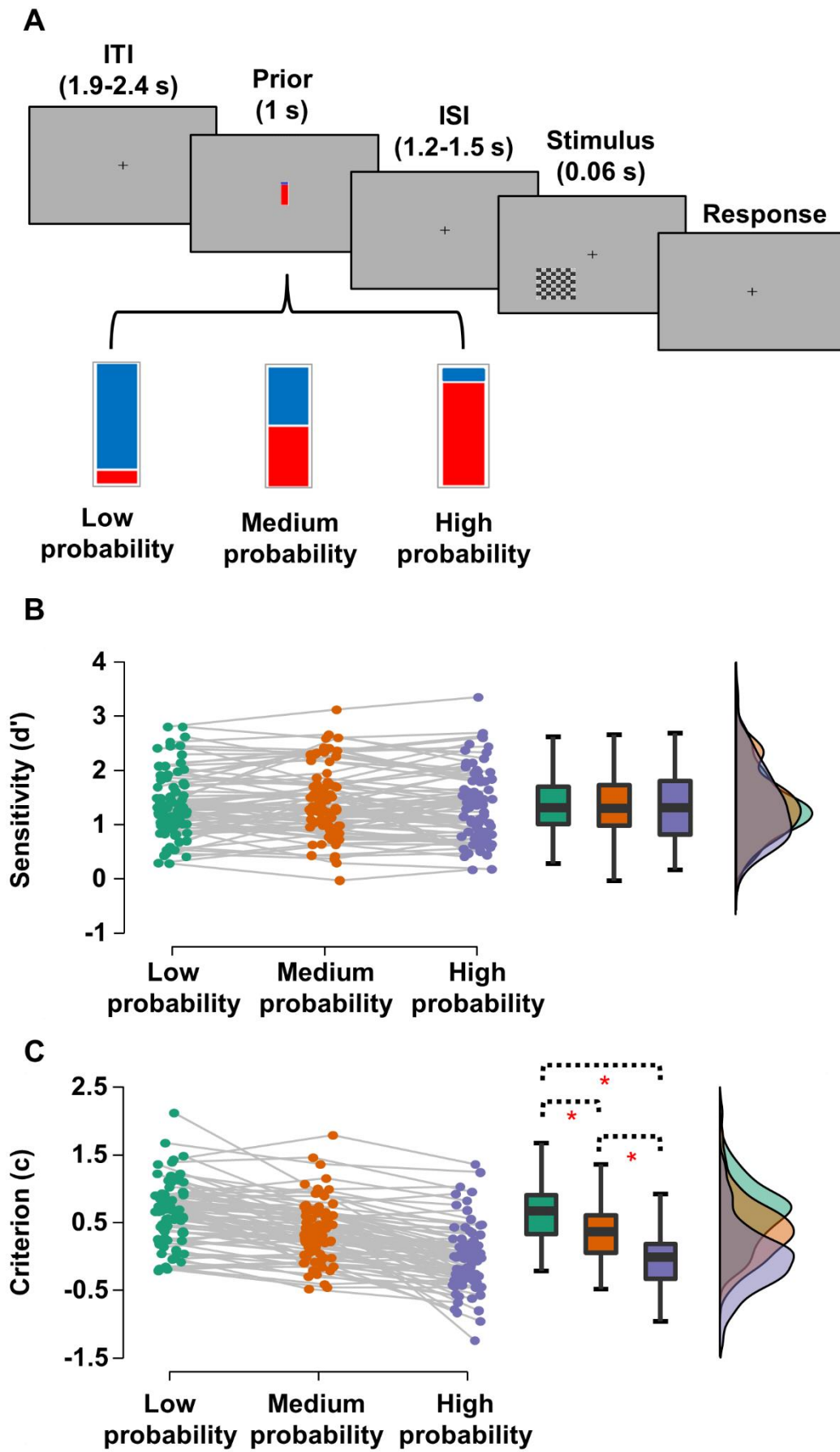


Figure 1.

A. Each trial started with the appearance of the cue presented at the centre of the screen for 1 s. The cue was a bar with its bottom colored in red and its top colored in blue. The amount of red in the bar indicated the probability of target's occurrence. High and low cue indicated the probability of target occurrence of 67 and 33%, respectively. Instead, the neutral cue equally predicted (50%) the target presence and absence. After a variable delay of 1.2–1.5 s a checkerboard containing (or not) grey circles appeared on the monitor. Participants pressed with the right hand the button associated with the choice. After response collection, the screen turned black for 1.9-2.4 s. The actual probability of target presentation was in accordance with the probability indicated by the cue, and participants were informed of this.

B. Prior information had no effect on perceptual sensitivity. C. On the contrary, the probabilistic cue shaped the decision criterion that gradually became more liberal as the probability of target presentation increased.

Results

Expectations modulate decision-making strategies

We computed the SDT indices d' and c to investigate the effect that prior information has on perceptual decision-making (Fig.1). The conducted analysis replicates the previous study by showing that priors affected the criterion ($F_{2,158} = 88.73; p < 0.01; \eta_p^2 = 0.53$) but not the sensitivity ($F_{2,158} = 1.22; p > 0.30; \eta_p^2 = 0.015$). Specifically, the participants adopted a more liberal criterion in trials preceded by high-probability cue ($c_{\text{high}} = -0.02 \pm 0.05$) relative to trials preceded by medium- ($c_{\text{mid}} = 0.37 \pm 0.05; t_{79} = -9.76, p < 0.01; d = -1.10$) and low-probability cue ($c_{\text{low}} = 0.63 \pm 0.05; t_{79} = -9.87, p < 0.01; d = -1.10$), in which the criterion were located in more conservative position relative to the neutral condition ($t_{79} = 7.15, p < 0.01; d = 0.80$). DDM parameters (Fig.S3) confirm these patterns of results: individuals increased the starting point in the high-probability trials relative to both medium- ($q < 0.01$) and low-probability trials ($q < 0.01$) and lowered the starting point in the low- relative to medium-probability trials ($q < 0.01$). We found no difference in the others DDM parameters.

Alpha oscillations track human decision-making strategies

We corroborated that the low- versus high-probability condition were associated to a different suppression of alpha amplitude in posterior regions (Fig.S5). Moreover, we assessed how individual differences over the tendency to shape alpha oscillations modulated the effect that prior exerted in decision-making. To this end, we partitioned the sample, through a median split approach (Fig.2A), between those who exhibited a strong reduction in alpha amplitude in the high- compared with the low-probability condition (i.e., the *believers*) versus those who showed a more nuanced modulation (i.e., the *empiricists*). The two groups showed different decision-making profiles: the prior-dependent modulation of the decision criterion ($\Delta \text{criterion}_{\text{believers}} = 0.88 \pm 0.10, \Delta \text{criterion}_{\text{empiricists}} = 0.42 \pm 0.07; t_{78} = 3.78, p < 0.01; d = 0.85$) were greater in individuals prone to shifting alpha amplitude (Fig.2B), while the sensitivity ($d'_{\text{believers}} = 1.41 \pm 0.10; d'_{\text{empiricists}} = 1.35 \pm 0.09; t_{78} = 0.40, p > 0.70; d = 0.09$) were not distinguishable between the two groups. This result was also supported by Pearson's correlation, which demonstrated that the degree of alpha modulation correlates positively with the level of Δ criterion (Fig.S5b). Furthermore, we verified that the alpha effect in tracking predictive styles is spatially localized to electrodes contralateral to stimulus presentation (Fig.2C). These findings proved the reliability of alpha fluctuations in detecting the different weights that prior knowledge plays in establishing decision-making biases in the general population.

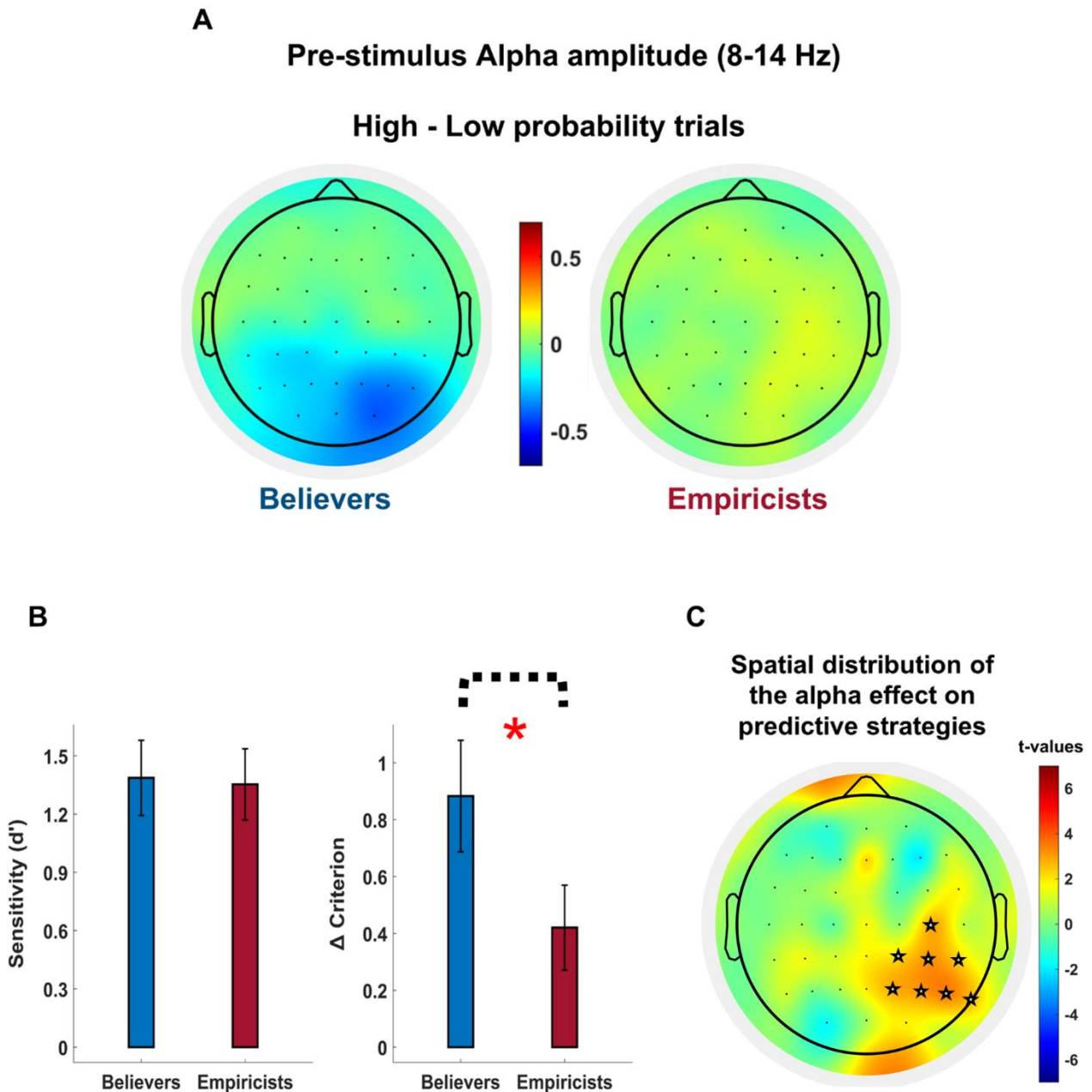


Figure 2. Electrophysiological correlates of prior processing.

- A. Topography of differential activations between the high- and low-probability conditions in the alpha band in the pre-stimulus window in the above- (believers) and below- (empiricists) median alpha modulators groups.
- B. The two groups exhibited undifferentiated sensitivity in the task. However, the decision-making strategy adopted was significantly different: while believers highly moderate the criterion according to the prior, empiricists are less constrained by it.
- C. Statistical analysis of the spatial specificity of the alpha effect in tracking individual predictive strategies. Stars mark the electrodes where pre-stimulus alpha oscillations significantly discriminate between the believer's and

empiricist's styles (see supplementary materials). This data-driven approach confirms a spatially localized effect mainly involving posterior cortical regions contralateral to stimulus presentation.

The individuals' position along the ASD-SSD axis drives the predictive strategy adopted.

To test whether individual position along the ASD-SSD axis could intercept the predictive style employed, we used principal component analysis to extract the component (i.e., PC2) showing opposite loading between the AQ and SPQ subscales (Table S2, Fig. S6). Then, we evaluated whether the PC2 individuals scores were significantly different between believers and empiricists. The independent sample t-test conducted showed the presence of a significant difference in the PC2 scores ($PC2_{\text{believers}} = 0.26 \pm 0.17$, $PC2_{\text{empiricists}} = -0.26 \pm 0.13$; $t_8 = 2.39$, $p = 0.02$; $d = 0.54$), proving that the believers were closer to the positive schizotypal end of the continuum, whereas the empiricists were more shifted toward the autistic pole of the continuum (Fig. 3; Fig. S7).

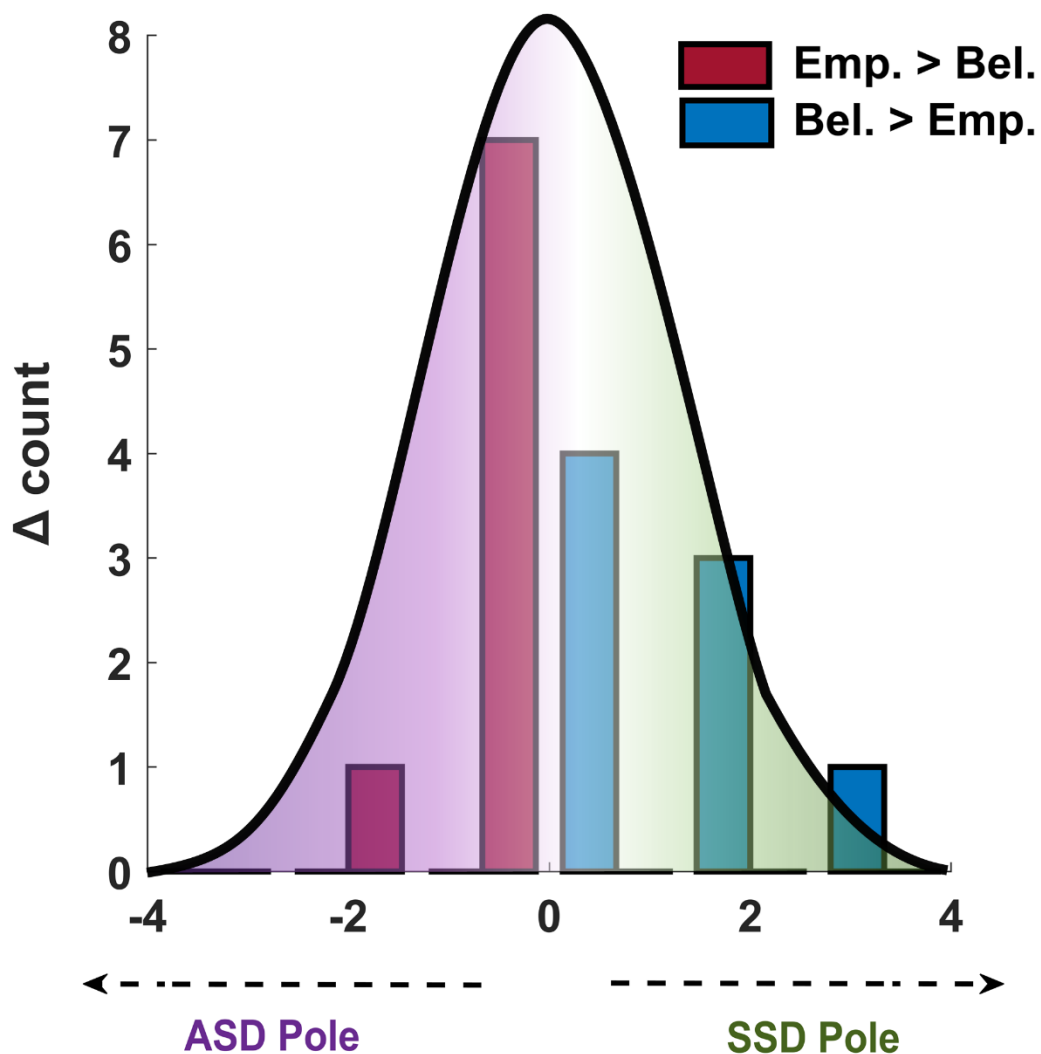


Figure 3. The position along the ASD-SSD continuum directs the adoption of the predictive strategy.

Individual scores concerning the ASD-SSD continuum factor are significantly different among the two groups. On the x-axis is represented the ASD-SSD continuum factor extracted through PCA, whereas on the y-axis is represented the difference between the number of believers and empirical participants. Believers were overrepresented in the schizotypal branch of the continuum ($PC2_{believers} = 0.26 \pm 0.17$), while empiricists ($PC2_{empiricists} = -0.26 \pm 0.13$) were placed more closely to the autistic pole of the continuum.

A very similar pattern of results emerged when comparing the AQ and SPQ subscale scores in the believers' group versus the empiricists' group (see supplementary materials): autistic and negative schizotypal traits exhibited a similar pattern of decision-making tendencies, being more prominent in the empiricist group (Fig.4A); conversely, positive schizotypal traits (e.g., magical thinking) were more present in the believers' group (Fig.4B).

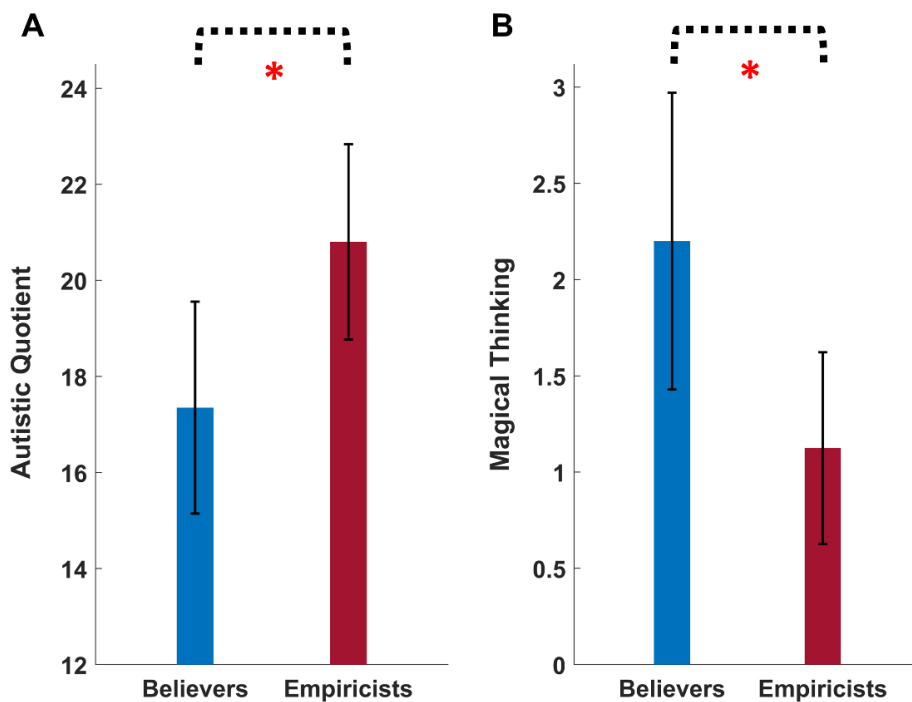


Figure 4. Positive autistic and schizotypal traits discriminate believers from empiricists.

- A. The number of autistic traits is higher in the cluster of individuals adopting the empiricist strategy ($AQ_{empiricists} = 20.80 \pm 1.00$) than in those adopting the believer strategy ($AQ_{believer} = 17.35 \pm 1.09$).
- B. Magical thinking is overrepresented in the cluster of individuals adopting the believer's strategy (Magical thinking_{believer} = 2.20 ± 0.38) than the ones embracing the empiricist's approach (Magical thinking_{empiricists} = 1.13 ± 0.25).

Correlation analysis

To corroborate the results obtained from the median-split analysis, we also showed that the PC2 score is significantly correlated with Δ alpha amplitude (Fig.S8; $r = 0.24, p = 0.03$), proving that the closer the individuals are to the schizotypal (vs. autistic) pole of the continuum, the more (vs. less) biases their alpha amplitude in a prior-dependent fashion. Similarly, we demonstrated the presence of a positive relationship between proximity to the schizotypal pole and the magnitude of criterion modulation in the high- vs. low-probability condition (Fig.S8; $r = 0.28, p = 0.01$). Then, we performed a multiple linear regression analysis to better understand the relation between these variables by placing the ASD-SSD continuum factor, the Δ Alpha Amplitude and the interaction between these two variables as predictors of Δ criterion. The analysis showed that the regression was significant ($F_{3,76} = 4.94, p < 0.01$), with both Δ alpha amplitude ($\beta = 0.26, p = 0.02$) and the ASD-SSD continuum factor ($\beta = 0.33, p = 0.02$) [but not their interaction ($\beta = -0.18, p = 0.17$)] emerged as significant predictors of the prior-based modulation of the decisional criterion (Δ criterion).

Mediation analysis

To further understand the inter-relation between ASD-SSD continuum factor, Δ criterion and Δ Alpha Amplitude, we conducted a mediation analysis to examine whether Δ Alpha Amplitude mediated any effect that the ASD-SSD continuum factor exerted on the Δ criterion (Fig.5). We found a significant mediation effect (0.04, 95% CI: 0.001 – 0.083), whereby relatively greater Δ Alpha Amplitude mediated the positive association between ASD-SSD continuum factor and Δ criterion (i.e., lower Δ criterion in individuals closer to the ASD pole). Moreover, the analysis showed that there was significant residual direct effect of ASD-SSD continuum factor on Δ criterion (0.13, 95% CI: 0.003 – 0.256) suggesting that the impact of ASD-SSD continuum factor on Δ criterion are partially mediated by the Δ Alpha Amplitude.

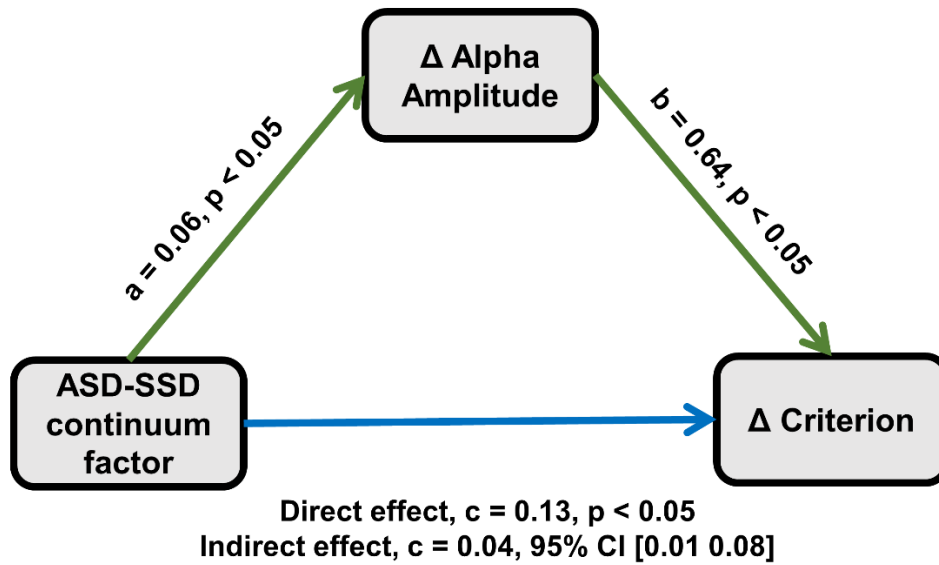


Figure 5. Mediation Analysis

Alpha amplitude modulation mediates the positive relationship between the ASD-SSD continuum factor and Δ criterion (i.e., higher Δ criterion in individuals closer to the SSD pole). Therefore, the relationship between the position along the continuum and the criterion is explained by the concurrent modulation that the ASD-SSD factor exert on alpha amplitude.

Discussion

Humans develop a constellation of different representations of the external world, even in the face of the same sensory experience^{6,28}. According to the Bayesian framework, these differentiations could be grounded on a different integration of prior knowledge with new information coming from the external world: some people are more prone to base their inferences on accumulated models and experiences, while others tend to rely more on input presented in the here and now. In this research, we explored whether these different predictive styles could be also routed by dispositional factors related to autistic and schizotypal traits. In accordance with the autism-schizophrenia continuum model⁹, ASD and SSD are associated with a diametrical behavioral/cognitive pattern resulting from a distinct weight given to priors and new sensory information²⁹⁻³¹. Positive SSD symptoms tend to be associated with priors-driven perception^{15,32,33} and opposition toward evidence that contradicts preconceived beliefs³⁴, whereas ASD is characterized by overweighting of external evidence^{11,35} compared to prior knowledge^{36,37}. Therefore, we expected that adopting a predictive style that overweights vs. underweights prior models may be prompted by a predominance of schizotypal vs. autistic traits, respectively.

To investigate these hypotheses, we used data from humans performing a probabilistic detection task, while non-invasively recording their neural activity using EEG. We have shown that providing prior knowledge about the target probability created a strong response bias in human observer, without affecting their visual sensitivity. However, the degree of bias-shifting was highly different among participants. Using the electrophysiological data collected, we were able to identify a neural signature that distinguish individuals that overweight (*believers*) vs. underweight (*empiricists*) expectation-like information in perceptual inference: *believers* showed extensive shaping of alpha oscillations in perceptual regions, while *empiricists* showed a reduced modulation. This finding proves that alpha rhythms are a reliable electrophysiological index able to discriminate participants' predictive behavior, confirming the role this frequency band plays in shaping perceptual outcomes^{8,38-42}. According to the SDT framework, observers evaluate the presence vs. the absence of the stimulus by assessing whether the strength of the internal responses exceeds the decisional criterion. Following this framework, a voluntary regulation of pre-stimulus alpha oscillations could impact the criterion through a modulation of the excitability of the cerebral cortex⁴³. The reduction of alpha amplitude in high- vs. low-probability trials would increase the cortical excitability that, in turn, would magnify the strength of the internal responses making it easier to exceed the decisional criterion^{4,40,44,45}.

Importantly, we analyzed whether individuals adopting the believer vs. empiricist strategies showed differences in schizotypal vs. autistic traits. First, we performed a PCA to extract the dimension showing opposite loading between the AQ and SPQ subscales. The conducted analysis showed that the second component (PC2) showed diametrical saturations with the positive schizotypal and autistic scales, confirming the opposite nature between these two dimensions²⁴⁻²⁷. Crucially, we identified that PC2 scores were statistically different in the two groups: the empiricists

showed negative mean values (i.e., they were more shifted toward the ASD pole), while the believers showed more positive values (i.e., they were more shifted toward the SSD pole).

It is important to emphasize that these findings contrast with some evidence pointing toward an opposite effect linked to reduced prior processing in SSD⁴⁶, as reflected by the reduced susceptibility to expectancy-driven illusions (e.g. the hollow-mask illusion⁴⁷). This conflicting evidence could be interpreted through a hierarchical model of predictive coding^{9,48-50}. According to this proposal, the weight assigned to predictive information in SSD could be subordinate to the hierarchical level from which it is generated: whereas predictions generated at lower levels of the cortical hierarchy (e.g., sensory areas) would have reduced precision, higher-order beliefs and explicit prior information (like the one employed in the current study) would be hyper-processed in the SSD population^{15,51}.

Furthermore, we corroborated the results highlighted by the PCA analysis by investigating the contribution of AQ and SPQ subscales in orienting the adoption of predictive styles. First, we demonstrated that participants within the believers group manifested less autistic and negative schizotypal traits compared to the empiricists. The finding that negative schizotypal traits share similarities in cognitive style with autistic traits is in line with empirical research showing the presence of comparable cognitive and perceptual phenomena that tie these two dimensions together. For example, both negative schizotypy and autistic traits predicted weaker rubber hand illusion effects^{52,53}. Subsequently, we showed that believers manifested higher rate of positive schizotypal traits relative to the empiricists. In particular, magical thinking was the subscale of the SPQ that was most strongly expressed in the believers' group. Magical thinking is connected with increased susceptibility to psychosis⁵⁴, anti-scientific attitudes⁵⁵, illusory perception⁵⁶⁻⁵⁸, and it is genetically connected to schizophrenia⁵⁹. Crucially, participants with higher magical ideation tend to rely on a limited amount of objective evidence to construct meaningful models, which are also overestimated⁶⁰, and showed decreased activity in the cognitive evaluation network during the processing of evidence that contradicts a belief⁶¹. Following these lines, a higher number of magical thinking would favor the adoption of the believer's style due to the propensity to promote the overestimation of the precision of prior knowledge, such as the expectation-like information provided in the task, at the expense of incoming information.

Finally, to better understand the relation between ASD-SSD continuum factor, Δ criterion and Δ Alpha Amplitude, we conducted a mediation analysis which proved that the influence exerted by the position along the ASD-SSD continuum on behavior was mediated by the degree of alpha amplitude modulation. This finding suggests that ASD and SSD traits could shape the use of probabilistic priors through opposite modulation on alpha wave amplitude⁶².

The described results fit into the growing literature aimed at identifying the behavioral and electrophysiological signatures underlying bayesian processing⁶³⁻⁶⁶ and inter-individual differences in the predictive machinery^{9,29,50,67}. For the first time, we have demonstrated that the position along the ASD-SSD continuum directs the predictive strategies adopted by individuals. This is particularly important because it shows that, even within the general population, it is possible to trace signs of the presence of different approaches toward predictive inference that depends on sub-clinical personality traits.

Future studies should investigate whether the directionality of the effect played by position along the ASD-SSD continuum is maintained even when interoceptive priors are introduced, given their role in modulating decision-making outcomes^{68,69}. It should be noted that, in the task employed, both strategies led to the same result in terms of accuracy. For this reason, we conceive these styles as two different, but equally valid, strategies within the proposed experimental set-up. Follow-up studies should investigate whether different contexts can elicit performance gains/losses as a function of the predictive style promoted by the ASD and SSD traits. For example, the tendency to favor the believer predictive style would explain why positive schizotypal traits were correlated with a performance advantage when the prior knowledge aid to interpret a highly ambiguous bottom-up signal⁷⁰, whereas the tendency to favor the empiricists predictive style would explain why AQ traits favor the perception of specific details when they are contained in global patterns⁷¹⁻⁷³. Moreover, since these peculiarities in information processing and in neural regulation are already evident in the sub-clinical population, they could be important factors both in identifying markers that signal early risk toward the development of mental disorders, and in understanding the mechanisms contributing to the onset of manifest clinical forms along the ASD-SSD continuum. In this regard, it would be crucial for future studies to evaluate the behavioral and neural indices outlined involving patients with positive SSD symptoms and ASD patients. This would allow to evaluate the developmental trajectory of predictive strategies, assessing whether they become more rigid, inflexible, and context-independent as one approaches the ends of the continuum.

Funding

This work was supported by #NEXTGENERATIONEU(NGEU) and funded by the Ministry of University and Research (MUR), National Recovery and Resilience Plan(NRRP), project MNESYS(PE0000006)–A Multiscale integrated approach to the study of the nervous system in health and disease(DN. 1553 11.10.2022)

Acknowledgments

The authors have no conflicts of interest to declare.

Reference

1. Helmholtz H von. *Handbuch der physiologischen Optik: mit 213 in den Text eingedruckten Holzschnitten und 11 Tafeln*. Voss; 1867.
2. Corlett PR, Horga G, Fletcher PC, Alderson-Day B, Schmack K, Powers AR. Hallucinations and Strong Priors. *Trends in Cognitive Sciences*. 2019;23(2):114-127. doi:10.1016/j.tics.2018.12.001
3. Pellicano E, Burr D. When the world becomes “too real”: a Bayesian explanation of autistic perception. *Trends Cogn Sci*. 2012;16(10):504-510. doi:10.1016/j.tics.2012.08.009
4. Tarasi L, di Pellegrino G, Romei V. Are you an empiricist or a believer? Neural signatures of predictive strategies in humans. *Progress in Neurobiology*. October 2022:102367. doi:10.1016/j.pneurobio.2022.102367
5. Samaha J, Iemi L, Postle BR. Prestimulus alpha-band power biases visual discrimination confidence, but not accuracy. *Conscious Cogn*. 2017;54:47-55. doi:10.1016/j.concog.2017.02.005
6. Benwell CSY, Mohr G, Wallberg J, Kouadio A, Ince RAA. Psychiatrically relevant signatures of domain-general decision-making and metacognition in the general population. *npj Mental Health Res*. 2022;1(1):1-17. doi:10.1038/s44184-022-00009-4
7. Limbach K, Corballis PM. Prestimulus alpha power influences response criterion in a detection task. *Psychophysiology*. 2016;53(8):1154-1164. doi:10.1111/psyp.12666
8. Di Gregorio F, Trajkovic J, Roperti C, et al. Tuning alpha rhythms to shape conscious visual perception. *Current Biology*. January 2022. doi:10.1016/j.cub.2022.01.003
9. Tarasi L, Romei V. Individual alpha frequency contributes to the precision of human visual processing. (In Press). *J Cogn Neurosci*. 2023.
10. Tarasi L, Trajkovic J, Diciotti S, et al. Predictive waves in the autism-schizophrenia continuum: A novel biobehavioral model. *Neuroscience & Biobehavioral Reviews*. 2022;132:1-22. doi:10.1016/j.neubiorev.2021.11.006
11. Van de Cruys S, Evers K, Van der Hallen R, et al. Precise minds in uncertain worlds: Predictive coding in autism. *Psychological Review*. 2014;121(4):649-675. doi:10.1037/a0037665
12. Karvelis P, Seitz AR, Lawrie SM, Seriès P. Autistic traits, but not schizotypy, predict increased weighting of sensory information in Bayesian visual integration. Stephan KE, ed. *eLife*. 2018;7:e34115. doi:10.7554/eLife.34115
13. Skewes JC, Jegindø EM, Gebauer L. Perceptual inference and autistic traits. *Autism*. 2015;19(3):301-307. doi:10.1177/1362361313519872
14. Ronconi L, Vitale A, Federici A, et al. Neural dynamics driving audio-visual integration in autism. *Cereb Cortex*. 2023;33(3):543-556. doi:10.1093/cercor/bhac083
15. Keehn B, Westerfield M, Müller RA, Townsend J. Autism, Attention, and Alpha Oscillations: An Electrophysiological Study of Attentional Capture. *Biol Psychiatry Cogn Neurosci Neuroimaging*. 2017;2(6):528-536. doi:10.1016/j.bpsc.2017.06.006
16. Schmack K, Gómez-Carrillo de Castro A, Rothkirch M, et al. Delusions and the Role of Beliefs in Perceptual Inference. *J Neurosci*. 2013;33(34):13701. doi:10.1523/JNEUROSCI.1778-13.2013

17. Kafadar E, Fisher VL, Quagan B, et al. Conditioned Hallucinations and Prior Overweighting Are State-Sensitive Markers of Hallucination Susceptibility. *Biological Psychiatry*. 2022;92(10):772-780. doi:10.1016/j.biopsych.2022.05.007
18. Powers AR, Mathys C, Corlett PR. Pavlovian conditioning–induced hallucinations result from overweighting of perceptual priors. *Science*. 2017;357(6351):596-600. doi:10.1126/science.aan3458
19. Kafadar E, Mittal VA, Strauss GP, et al. Modeling perception and behavior in individuals at clinical high risk for psychosis: Support for the predictive processing framework. *Schizophrenia Research*. 2020;226:167-175. doi:10.1016/j.schres.2020.04.017
20. Billeke P, Armijo A, Castillo D, et al. Paradoxical Expectation: Oscillatory Brain Activity Reveals Social Interaction Impairment in Schizophrenia. *Biological Psychiatry*. 2015;78(6):421-431. doi:10.1016/j.biopsych.2015.02.012
21. Green DM, Swets JA. *Signal Detection Theory and Psychophysics*. Oxford, England: John Wiley; 1966:xi, 455.
22. Wiecki T, Sofer I, Frank M. HDDM: Hierarchical Bayesian estimation of the Drift-Diffusion Model in Python. *Frontiers in Neuroinformatics*. 2013;7:14. doi:10.3389/fninf.2013.00014
23. Baron-Cohen S, Wheelwright S, Skinner R, Martin J, Clubley E. The Autism-Spectrum Quotient (AQ): Evidence from Asperger Syndrome/High-Functioning Autism, Males and Females, Scientists and Mathematicians. *J Autism Dev Disord*. 2001;31(1):5-17. doi:10.1023/A:1005653411471
24. Raine A. The SPQ: A Scale for the Assessment of Schizotypal Personality Based on DSM-III-R Criteria. *Schizophrenia Bulletin*. 1991;17(4):555-564. doi:10.1093/schbul/17.4.555
25. Dinsdale NL, Hurd PL, Wakabayashi A, Elliot M, Crespi BJ. How Are Autism and Schizotypy Related? Evidence from a Non-Clinical Population. *PLOS ONE*. 2013;8(5):e63316. doi:10.1371/journal.pone.0063316
26. Zhou H yu, Yang H xue, Gong J bo, et al. Revisiting the overlap between autistic and schizotypal traits in the non-clinical population using meta-analysis and network analysis. *Schizophrenia Research*. 2019;212:6-14. doi:10.1016/j.schres.2019.07.050
27. Nenadić I, Meller T, Evermann U, et al. Subclinical schizotypal vs. autistic traits show overlapping and diametrically opposed facets in a non-clinical population. *Schizophrenia Research*. 2021;231:32-41. doi:10.1016/j.schres.2021.02.018
28. Del Giudice M, Klimczuk ACE, Traficante DM, Maestripieri D. Autistic-like and schizotypal traits in a life history perspective: Diametrical associations with impulsivity, sensation seeking, and sociosexual behavior. *Evolution and Human Behavior*. 2014;35:415-424. doi:10.1016/j.evolhumbehav.2014.05.007
29. Karlaftis VM, Giorgio J, Vértes PE, et al. Multimodal imaging of brain connectivity reveals predictors of individual decision strategy in statistical learning. *Nat Hum Behav*. 2019;3(3):297-307. doi:10.1038/s41562-018-0503-4
30. Andersen BP. Autistic-Like Traits and Positive Schizotypy as Diametric Specializations of the Predictive Mind. *Perspect Psychol Sci*. July 2022:17456916221075252. doi:10.1177/17456916221075252

31. Tarasi L, Magosso E, Ricci G, Ursino M, Romei V. The Directionality of Fronto-Posterior Brain Connectivity Is Associated with the Degree of Individual Autistic Traits. *Brain Sciences*. 2021;11(11):1443. doi:10.3390/brainsci11111443
32. Ursino M, Serra M, Tarasi L, Ricci G, Magosso E, Romei V. Bottom-up vs. top-down connectivity imbalance in individuals with high-autistic traits: An electroencephalographic study. *Front Syst Neurosci*. 2022;16:932128. doi:10.3389/fnsys.2022.932128
33. Stuke H, Kress E, Weilhhammer VA, Sterzer P, Schmack K. Overly Strong Priors for Socially Meaningful Visual Signals Are Linked to Psychosis Proneness in Healthy Individuals. *Frontiers in Psychology*. 2021;12:1083. doi:10.3389/fpsyg.2021.583637
34. Powers AR, Kelley M, Corlett PR. Hallucinations as top-down effects on perception. *Biol Psychiatry Cogn Neurosci Neuroimaging*. 2016;1(5):393-400. doi:10.1016/j.bpsc.2016.04.003
35. Woodward TS, Buchy L, Moritz S, Liotti M. A Bias Against Disconfirmatory Evidence Is Associated With Delusion Proneness in a Nonclinical Sample. *Schizophr Bull*. 2007;33(4):1023-1028. doi:10.1093/schbul/sbm013
36. Brock J. Alternative Bayesian accounts of autistic perception: comment on Pellicano and Burr. *Trends in Cognitive Sciences*. 2012;16(12):573-574. doi:10.1016/j.tics.2012.10.005
37. Schneebeli M, Haker H, Rüesch A, et al. Disentangling “Bayesian brain” theories of autism spectrum disorder. February 2022:2022.02.07.22270242. doi:10.1101/2022.02.07.22270242
38. von der Lühe T, Manera V, Barisic I, Becchio C, Vogeley K, Schilbach L. Interpersonal predictive coding, not action perception, is impaired in autism. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2016;371(1693):20150373. doi:10.1098/rstb.2015.0373
39. Romei V, Gross J, Thut G. On the Role of Prestimulus Alpha Rhythms over Occipito-Parietal Areas in Visual Input Regulation: Correlation or Causation? *J Neurosci*. 2010;30(25):8692-8697. doi:10.1523/JNEUROSCI.0160-10.2010
40. Cecere R, Rees G, Romei V. Individual Differences in Alpha Frequency Drive Crossmodal Illusory Perception. *Current Biology*. 2015;25(2):231-235. doi:10.1016/j.cub.2014.11.034
41. Samaha J, Iemi L, Haegens S, Busch NA. Spontaneous Brain Oscillations and Perceptual Decision-Making. *Trends in Cognitive Sciences*. 2020;24(8):639-653. doi:10.1016/j.tics.2020.05.004
42. Ronconi L, Busch NA, Melcher D. Alpha-band sensory entrainment alters the duration of temporal windows in visual perception. *Sci Rep*. 2018;8(1):11810. doi:10.1038/s41598-018-29671-5
43. Ippolito G, Bertaccini R, Tarasi L, et al. The Role of Alpha Oscillations among the Main Neuropsychiatric Disorders in the Adult and Developing Human Brain: Evidence from the Last 10 Years of Research. *Biomedicines*. 2022;10(12):3189. doi:10.3390/biomedicines10123189
44. Jensen O, Mazaheri A. Shaping Functional Architecture by Oscillatory Alpha Activity: Gating by Inhibition. *Frontiers in Human Neuroscience*. 2010;4:186. doi:10.3389/fnhum.2010.00186
45. Iemi L, Chaumon M, Crouzet SM, Busch NA. Spontaneous Neural Oscillations Bias Perception by Modulating Baseline Excitability. *J Neurosci*. 2017;37(4):807-819. doi:10.1523/JNEUROSCI.1432-16.2016

46. Foxe JJ, Snyder AC. The Role of Alpha-Band Brain Oscillations as a Sensory Suppression Mechanism during Selective Attention. *Front Psychol.* 2011;2:154. doi:10.3389/fpsyg.2011.00154
47. Valton V, Karvelis P, Richards KL, Seitz AR, Lawrie SM, Seriès P. Acquisition of visual priors and induced hallucinations in chronic schizophrenia. *Brain.* 2019;142(8):2523-2537. doi:10.1093/brain/awz171
48. Dima D, Roiser JP, Dietrich DE, et al. Understanding why patients with schizophrenia do not perceive the hollow-mask illusion using dynamic causal modelling. *Neuroimage.* 2009;46(4):1180-1186. doi:10.1016/j.neuroimage.2009.03.033
49. Stuke H, Weilhhammer VA, Sterzer P, Schmack K. Delusion Proneness is Linked to a Reduced Usage of Prior Beliefs in Perceptual Decisions. *Schizophrenia Bulletin.* 2019;45(1):80-86. doi:10.1093/schbul/sbx189
50. Schmack K, Rothkirch M, Priller J, Sterzer P. Enhanced predictive signalling in schizophrenia. *Human Brain Mapping.* 2017;38(4):1767-1779. doi:10.1002/hbm.23480
51. Sterzer P, Adams RA, Fletcher P, et al. The Predictive Coding Account of Psychosis. *Biological Psychiatry.* 2018;84(9):634-643. doi:10.1016/j.biopsych.2018.05.015
52. Haarsma J, Knolle F, Griffin JD, et al. Influence of prior beliefs on perception in early psychosis: Effects of illness stage and hierarchical level of belief. *Journal of Abnormal Psychology.* 2020;129(6):581. doi:10.1037/abn0000494
53. Ide M, Wada M. Salivary Oxytocin Concentration Associates with the Subjective Feeling of Body Ownership during the Rubber Hand Illusion. *Frontiers in Human Neuroscience.* 2017;11. <https://www.frontiersin.org/articles/10.3389/fnhum.2017.00166>. Accessed November 17, 2022.
54. Torregrossa LJ, Park S. Body ownership across schizotypy dimensions: A rubber hand illusion experiment. *Psychiatry Research Communications.* 2022;2(3):100058. doi:10.1016/j.psychom.2022.100058
55. Chapman LJ, Chapman JP, Kwapil TR, Eckblad M, Zinser MC. Putatively psychosis-prone subjects 10 years later. *Journal of Abnormal Psychology.* 1994;103:171-183. doi:10.1037/0021-843X.103.2.171
56. Tarasi L, Borgomaneri S, Romei V. Antivax attitude in the general population along the autism-schizophrenia continuum and the impact of socio-demographic factors. *Frontiers in Psychology.* 2023;14. <https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1059676>. Accessed February 18, 2023.
57. Elk M van. Paranormal believers are more prone to illusory agency detection than skeptics. *Consciousness and Cognition.* 2013;22(3):1041-1046. doi:10.1016/j.concog.2013.07.004
58. Riekkari T, Lindeman M, Aleneff M, Halme A, Nuortimo A. Paranormal and Religious Believers Are More Prone to Illusory Face Perception than Skeptics and Non-believers. *Applied Cognitive Psychology.* 2013;27(2):150-155. doi:10.1002/acp.2874
59. Peled A, Ritsner M, Hirschmann S, Geva AB, Modai I. Touch feel illusion in schizophrenic patients. *Biological Psychiatry.* 2000;48(11):1105-1108. doi:10.1016/S0006-3223(00)00947-1
60. Saarinen A, Lyytikäinen LP, Hietala J, et al. Magical thinking in individuals with high polygenic risk for schizophrenia but no non-affective psychoses—a general population study. *Mol Psychiatry.* May 2022:1-8. doi:10.1038/s41380-022-01581-z

61. Brugger P, Graves RE. Testing vs. Believing Hypotheses: Magical Ideation in the Judgement of Contingencies. *Cognitive Neuropsychiatry*. 1997;2(4):251-272. doi:10.1080/135468097396270
62. Lavigne KM, Menon M, Moritz S, Woodward TS. Functional brain networks underlying evidence integration and delusional ideation. *Schizophrenia Research*. 2020;216:302-309. doi:10.1016/j.schres.2019.11.038
63. Martínez A, Tobe R, Dias EC, et al. Differential patterns of visual sensory alteration underlying face emotion recognition impairment and motion perception deficits in schizophrenia and autism spectrum disorders. *Biol Psychiatry*. 2019;86(7):557-567. doi:10.1016/j.biopsych.2019.05.016
64. Friedrich EVC, Zillekens IC, Biel AL, et al. Seeing a Bayesian ghost: Sensorimotor activation leads to an illusory social perception. *iScience*. 2022;25(4):104068. doi:10.1016/j.isci.2022.104068
65. Bastos AM, Lundqvist M, Waite AS, Kopell N, Miller EK. Layer and rhythm specificity for predictive routing. *Proc Natl Acad Sci USA*. 2020;117(49):31459-31469. doi:10.1073/pnas.2014868117
66. Betti V, Della Penna S, de Pasquale F, Corbetta M. Spontaneous Beta Band Rhythms in the Predictive Coding of Natural Stimuli. *Neuroscientist*. 2021;27(2):184-201. doi:10.1177/1073858420928988
67. Dzafic I, Larsen KM, Darke H, et al. Stronger Top-Down and Weaker Bottom-Up Frontotemporal Connections During Sensory Learning Are Associated With Severity of Psychotic Phenomena. *Schizophrenia Bulletin*. 2021;47(4):1039-1047. doi:10.1093/schbul/sbaa188
68. Powers AR, Corlett PR, Ross DA. Guided by Voices: Hallucinations and the Psychosis Spectrum. *Biol Psychiatry*. 2018;84(6):e43-e45. doi:10.1016/j.biopsych.2018.07.015
69. Migeot JA, Duran-Aniotz CA, Signorelli CM, Piguet O, Ibáñez A. A predictive coding framework of allostatic-interoceptive overload in frontotemporal dementia. *Trends in Neurosciences*. 2022;45(11):838-853. doi:10.1016/j.tins.2022.08.005
70. Salamone PC, Legaz A, Sedeño L, et al. Interoception Primes Emotional Processing: Multimodal Evidence from Neurodegeneration. *J Neurosci*. 2021;41(19):4276-4292. doi:10.1523/JNEUROSCI.2578-20.2021
71. Teufel C, Subramaniam N, Dobler V, et al. Shift toward prior knowledge confers a perceptual advantage in early psychosis and psychosis-prone healthy individuals. *PNAS*. 2015;112(43):13401-13406. doi:10.1073/pnas.1503916112
72. Cribb SJ, Olaithe M, Di Lorenzo R, Dunlop PD, Maybery MT. Embedded Figures Test Performance in the Broader Autism Phenotype: A Meta-analysis. *J Autism Dev Disord*. 2016;46(9):2924-2939. doi:10.1007/s10803-016-2832-3
73. Russell-Smith SN, Maybery MT, Bayliss DM, Sng AAH. Support for a Link Between the Local Processing Bias and Social Deficits in Autism: An Investigation of Embedded Figures Test Performance in Non-Clinical Individuals. *J Autism Dev Disord*. 2012;42(11):2420-2430. doi:10.1007/s10803-012-1506-z
74. Conson M, Senese VP, Zappullo I, et al. The effect of autistic traits on disembedding and mental rotation in neurotypical women and men. *Sci Rep*. 2022;12(1):4639. doi:10.1038/s41598-022-08497-2