Clinical Neurophysiology 166 (2024) 87–95

Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Corollary discharge and anomalous self-experiences in schizophrenia and bipolar disorder: A specificity analysis

Rosa M. Beño-Ruiz-de-la-Sierra [a,1], Antonio Arjona-Valladares [a,1], Marta Hernández-García [b], Inés Fernández-Linsenbarth [a], Álvaro Díez [a], Alejandro Roig-Herrero [a,c], Emma Osorio-Iriarte [a], Vicente Molina [a,b,*]

[a] Psychiatry Department, School of Medicine, University of Valladolid, Spain
[b] Psychiatry Service, University Clinical Hospital of Valladolid, Spain
[c] Imaging Processing Laboratory, University of Valladolid, Spain

HIGHLIGHTS

- Suppression of N1 event-related potential during speech was significantly reduced in schizophrenia patients.
- Bipolar disorder patients exhibited intermediate sensory attenuation between the schizophrenia and control group.
- The extent of N1 suppression inversely correlated with the severity of Anomalous Self-Experiences in schizophrenia, but not in bipolar disorder.

ARTICLE INFO

Article history:
Accepted 26 July 2024
Available online 2 August 2024

Keywords:
Event-Related Potentials
Auditory N1
Suppression
Speech
Ipseity
Psychosis

ABSTRACT

Objective: The Corollary Discharge (CD) mechanism inhibits self-generated speech sound perception, appearing disrupted in schizophrenia and potentially contributing to Anomalous Self-Experiences (ASEs). However, it remains unclear if this alteration and its correlation with ASEs extend to other psychotic disorders.
Methods: Electroencephalography was used to study the N1 Event-Related Potential (ERP) as an index of CD-mediated suppression in the auditory cortex across thirty-five participants with schizophrenia, twenty-six with bipolar disorder, and thirty healthy controls. Auditory N1 was elicited by two conditions: real-time listening to self-pronounced vowels while speaking through connected microphone and earphones (*listen/talk* –or *talk* condition in previous literature-) and passive listening to the same previously recorded self-uttered vowels (*listen/no talk* –or *listen* condition-).
Results: N1 ERP amplitude was lower in the *listen/talk* condition compared to *listen/no talk* across all groups. However, N1 suppression was significantly reduced in schizophrenia, with bipolar patients showing intermediate attenuation between both groups (i.e., non-significantly different from controls). Furthermore, N1 suppression inversely correlated with ASEs severity only in schizophrenia.
Conclusions: Dysfunction of the CD mechanism may be a defining feature of schizophrenia, where it is connected to ASEs.
Significance: These results corroborate previous findings linking auditory N1 ERP suppression with disrupted CD mechanism in schizophrenia, but not in bipolar disorder.

1. Introduction

Distinguishing sensations caused by our actions from those of external origin is a basic element of adequate cognitive and motor functioning. Corollary discharge is neural mechanism by which the sensory consequences of self-initiated acts are attenuated or suppressed (Sperry, 1950) so it probably underlies such a distinction. The integrity of the corollary discharge mechanism is essential for developing a sense of agency over psychomotor experiences and for ensuring coherence in our interactions with the surrounding world (Beño-Ruiz-de-la-Sierra et al., 2023a; Poletti et al., 2019). A failure of the corollary discharge mechanism could impair the ability to recognize self-generated actions, resulting in their misattribution to external sources (Feinberg, 1978).

* Corresponding author at: Dept. of Psychiatry, School of Medicine, University of Valladolid. Av. Ramón y Cajal, 7, Valladolid 48005, Spain.
E-mail address: vicente.molina@uva.es (V. Molina).
[1] These authors contributed equally to the article.

https://doi.org/10.1016/j.clinph.2024.07.014
1388-2457/

In the context of a vocalization activity, the activation of the corollary discharge mechanism follows a feed-forward inhibitory process in which interneurons located in the auditory cortex inhibit pyramidal neurons and, as a result, cortical responses arising from self-generated speech are effectively suppressed (Eliades and Wang, 2008; Nelson et al., 2013; Reznik and Mukamel, 2019; Schneider et al., 2014). One way to assess the corollary discharge is by using the N1 potential elicitation through a two-condition task: i) a concurrent listening to self-pronounced vowels (*listen/talk* condition) and ii) a subsequent non-concurrent listening to the same previously self-uttered vowels (*listen/no talk* condition). These conditions have also been called *talk* and *listen* conditions, respectively, in previous literature (Ford et al., 2010). Under this electrophysiological paradigm, N1 shows a marked decrease when individuals actively listen to their own voice while speaking, whereas it is preserved when they passively listen to a recording of their own voice (Beño-Ruiz-de-la-Sierra et al., 2023a; Hubl et al., 2014; Wang et al., 2014). This mechanism enables a preconscious differentiation of the source of sensory input, which would probably play a role in self-identification.

The close connection between corollary discharge integrity and motor development strongly indicates that disruptions in corollary discharge mechanism may arise early in neurodevelopment, increasing the risk of later psychotic states (Poletti et al., 2019). An early altered corollary discharge mechanism may interfere with the early, prereflective implicit alignment of an individual's sensorimotor actions with the surrounding world, contributing to the emergence of self-disorders (Poletti et al., 2019).

The ipseity disturbance is a core abnormality described in schizophrenia as an alteration in the tacit, preconscious experience of being the subject owner of conscious processes. In other words, this ipseity alteration is a disturbance of the mode of naturally inhabiting one's own mental experience. Two main aspects of this ipseity disturbance are the experience of hyper-reflexivity (i.e., exaggerated self-consciousness involving self-alienation) and a diminished self-affection (i.e., diminished intensity of one's own subjective self-presence) (Sass and Parnas, 2003). Anomalous Self-Experiences (ASEs) are a noteworthy phenomenon in people with psychosis (Raballo et al., 2011), even during their initial stages (Haug et al., 2014) and in at-risk states (Madeira et al., 2016), showing a marked temporal stability (Nordgaard et al., 2018). ASEs are manifested as a disruption or loss of the innate preconscious cues that allow us to recognize our mental contents as our own, encompassing both cognitive and somatic dimensions, and to differentiate them from the external world (Nelson et al., 2014; Raballo and Parnas, 2012). In previous studies, the severity of these experiences in people with schizophrenia has been significantly related to alterations in their cognitive performance (Hernández-García et al., 2021; Nelson et al., 2020), in functional connectivity patterns between brain regions, measured by a resting-state functional Magnetic Resonance Imaging (rs_fMRI) (Roig-Herrero et al., 2022), and also to aberrant functional interactions involving the right ventral premotor cortex and bilateral posterior insula with the posterior cingulate cortex (Ebisch et al., 2014). Considering its preconscious nature and the previous literature exposed, it is plausible that ASEs may be associated with some neural alterations, with a deficient corollary discharge mechanism being a possible substrate for these experiences (Beño-Ruiz-de-la-Sierra et al., 2023b).

Alterations in the corollary discharge mechanism have been consistently reported in schizophrenia as a significant reduction of the N1 suppression (for a review see Whitford, 2019), and corollary discharge has been proposed as a transdiagnostic mechanism of psychosis (Ford et al., 2013; Yao et al., 2024). This lack of suppression of self-generated stimuli has been previously related to the severity of positive and negative symptoms and ASEs in people with schizophrenia (Beño-Ruiz-de-la-Sierra et al., 2023b). However, it remains unclear whether these deficits in the expression of corollary discharge and their relationship to ASEs are specific to schizophrenia or whether they are also seen in other psychosis spectrum disorders. To our notice, only one study assessed the auditory sensory attenuation during speech in bipolar disorder, also reporting a reduced N1 suppression (Ford et al., 2013), but its association with ASEs has not been previously assessed. Therefore, the main objective of the present study was to evaluate the expression in the N1 potential of the corollary discharge mechanism in people with bipolar disorder and its association with the severity of ASEs, so that we can assess its specificity within the diagnosis of schizophrenia. To this end, we first compared the corollary discharge effect between patients with different psychotic diagnoses (schizophrenia and bipolar disorder) and healthy controls, using Electroencephalography (EEG) and comparing the suppression of the N1 auditory potential between *listen/talk* and *listen/no talk* conditions. In a second step, the relationship between these alterations and ASEs was examined.

2. Materials and methods

2.1. Sample

Thirty-five participants with schizophrenia (21 male / 14 female; age range 20–55 years), twenty-six participants with bipolar disorder (14 male / 12 female; age range 18–60 years), and thirty healthy controls (15 male / 15 female; age range 20–54 years), all with normal hearing, participated in the study. All bipolar participants were diagnosed with bipolar I disorder and had a history of psychotic symptoms during their manic episodes. The EEG data were acquired during a euthymic phase following a hospital admission due to their last manic episode. Patients were diagnosed by an expert psychiatrist (VM) according to the fifth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5). Exclusion criteria were (i) neurological disease, (ii) history of head trauma with loss of consciousness, (iii) current substance abuse (except nicotine or caffeine), (iv) Intelligence Quotient (IQ) less than 70, and (v) any psychiatric treatment (for controls) or (vi) current diagnosis other than schizophrenia or bipolar disorder (for patients). Sociodemographic, clinical, cognitive, and neurophysiological data are shown in Table 1. All participants gave written informed consent after receiving complete printed information. The ethical committee of the participating hospital endorsed the study.

2.2. Cognitive and clinical assessment

Patients' positive and negative symptoms were respectively assessed using the positive subscale of the 'Positive and Negative Syndrome Scale for Schizophrenia' (PANSS) (Kay et al., 1987), and the 'Brief Negative Symptom Scale' (BNSS) (Kirkpatrick et al., 2011). Cognitive performance was assessed using the Spanish version of the 'Brief Assessment in Cognition in Schizophrenia Scale' (BACS) (Keefe et al., 2008; Segarra et al., 2011), and the 'Wisconsin Card Sorting Test' (WCST: percentage of perseverative errors) (Chelune and Baer, 1986). IQ was estimated using the 'Wechsler Adult Intelligence Scale-III' (WAIS-III) (Durá et al., 2010; Wechsler, 1997). The cognitive and clinical assessment was done for descriptive purposes to ensure that patients have equivalent impairment to that of our previous studies.

Table 1
Sociodemographic, cognition, clinical characteristics, and neurophysiological values of the participants.

	Healthy controls n = 30	Schizophrenia n = 35	Bipolar disorder n = 26
Sex (M/F)	15/15	21/14	14/12
Age (years)	32.43 (9.64)	37.17 (11.18)	38.96 (12.46)
Education (years)	15.83 (2.19)	13.15 (3.32)	14.46 (2.50)
Illness duration (months)	–	75.77 (111.71)	186.64 (135.40)
CPZ equivalents (mg)	–	406.30 (292.37)	240.58 (198.28)
IPASE-Total ASEs	–	126.40 (50.11)	112.43 (43.57)
IPASE-Cognition	–	14.77 (6.70)	11.70 (5.19)
IPASE-Self Awareness and Presence	–	48.53 (21.75)	45.00 (19.64)
IPASE-Consciousness	–	14.50 (6.49)	13.00 (6.56)
IPASE-Somatization	–	38.20 (13.69)	33.43 (12.84)
IPASE-Demarcation/Transitivism	–	10.33 (4.77)	9.30 (4.19)
PANSS-Positive symptoms	–	12.97 (5.10)	8.50 (2.45)
BNSS-Negative symptoms	–	19.94 (12.31)	9.04 (11.95)
WAIS-Total IQ	110.32 (9.32)	93.57 (15.13)***	96.81 (11.43)***
BACS-Verbal memory	53.54 (8.22)	41.88 (12.45)***	41.62 (10.15)***
BACS-Working memory	22.50 (3.36)	18.44 (5.13)***	18.31 (3.91)***
BACS-Motor speed	74.54 (14.55)	58.03 (12.36)***	56.85 (12.32)***
BACS-Verbal fluency	27.19 (4.86)	21.39 (6.35)***	21.60 (4.74)***
BACS-Processing fluency	67.25 (9.60)	46.74 (14.34)***	45.31 (13.36)***
BACS-Problem solving	18.12 (2.56)	16.94 (3.20)	16.81 (2.61)
WCST-Perseverative errors (%)	8.40 (2.93)	12.35 (8.35)*	14.82 (8.10)***
N1 suppression (μV)	4.41 (3.63)	1.34 (2.15)***	3.00 (3.22)
Usable trials in TK	128.40 (45.85)	122.67 (48.94)	126.65 (65.98)
Usable trials in LS	129.23 (46.93)	129.61 (44.90)	147.38 (53.18)

Note: Data are given as mean (standard deviation). Neurophysiological value of N1 corresponds to FCz electrode.
Abbreviations: M/F, Masculine/Feminine; CPZ, Chlorpromazine; IPASE, Inventory of Psychotic-Like Anomalous Self-Experiences; ASEs, Anomalous Self-Experiences; PANSS, Positive and Negative Syndrome Scale; BNSS, Brief Negative Symptom Scale; WAIS, Wechsler Adult Intelligence Scale; IQ, Intelligence Quotient; BACS, Brief Assessment of Cognition in Schizophrenia; WCST, Wisconsin Card Sorting Test; TK, *Listen/talk* condition; LS, *Listen/no talk* condition.
*p < 0.05; **p < 0.01; ***p < 0.001 (Chi square test, Student's test or Mann-Whitney when corresponding) in comparison to healthy controls.

2.3. Anomalous self-experiences (ASEs) assessment

ASEs were assessed using the 'The Inventory of Psychotic-Like Anomalous Self-Experiences – IPASE' (Cicero et al., 2017), a 57-item self-report scale with a 5-factor structure. Here, patients, in the presence of the researcher, rate their agreement with statements on a scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The factors include: *Cognition*, focusing on thought process difficulties like thought interference; *Self-Awareness and Presence*, covering aspects related to loss of self or basic identity and disconnection from the world; *Consciousness*, encompassing alterations in time perception, intentionality, and difficulty discerning between imagination and reality; *Somatization*, addressing disturbances in bodily experiences such as changes in body shape or lack of control, and feelings of physical or psychological absence from one's own body; and *Demarcation/Transitivism*, concerning the dissolution of boundaries between self and world or a sense of nonexistence.

2.4. Neurophysiological evaluation of the corollary discharge mechanism

Participants were seated 60 cm (cm) from a computer screen with a white cross in the center of a black background. Each participant completed two distinct conditions (Ford et al., 2010):

- *Listen/talk* condition (i.e., *talk* condition in previous literature): a microphone (model NT1) was positioned 15 cm from the participant's mouth and participants were instructed to vocalize the phoneme [a:] at intervals of approximately every 1–2 s for a duration of 4 min, with a 30-second rest after the initial two minutes. Concurrently, the microphone captured the vocalizations, which were then amplified and relayed to the participant in real-time through headphones (model SE215).
- *Listen/no talk* condition (i.e., *listen* condition in previous literature): Subsequently, participants were instructed to listen passively to their previously recorded vocalizations from the *listen/talk* condition, also presented through headphones.

Prior to recording the *listen/talk* condition, participants received detailed instructions regarding maintaining a consistent 15 cm distance from the microphone, brief (<300 ms) vocalization of the phoneme [a:] and maintaining a volume between 65 and 75 dB (dB) Sound Pressure Level (SPL). Immediate feedback on performance was provided during this training phase. Participants were instructed to minimize movement, remain still, open their mouths before vocalizing, maintain fixation on the fixation cross throughout the recording, and sustain a steady vocal tone. Choosing a vowel rather than a more complex sound has the advantage of introducing less muscle noise into the EEG recordings. Additionally, the cognitive processing associated with the pronunciation of a single vowel is quite low because it does not convey any semantic information.

Volume intensity was continuously monitored using a calibrated sound level meter (model PCE-353 N-ICA) positioned 6 cm from the mouth. Volume standardization across conditions was achieved based on the balance of headphone audio output, meticulously measured with a dB-meter (Ford et al., 2010). During the *listen/talk* condition, the signal corresponding to each vocalization was transmitted through an audio interface (Focusrite®) to a sound processing software (Audacity®) and to a stimulation tracker (StimTrak: Brain vision) which transforms this signal into a trigger pulse and sends it to the EEG preamplifier (actiCHamp). These trigger pulses, generated on the rising edge of the rectified signal, were integrated into the EEG recordings. The sensitivity level of the amplifier was set up to generate triggers only when a minimum of 65 dB voice volume was generated by the participant. Vocalizations falling outside the 65–75 dB range were excluded from the

analysis. To mitigate the influence of bone conduction during vocalization, the mean speech SPL presented through headphones was elevated by 15 dB above each participant's mean speech SPL in both conditions (Ford et al., 2007; Heinks-Maldonado et al., 2007).

The corollary discharge effect was assessed as the difference in amplitude of N1 corresponding to the *listen/talk* condition minus the *listen/no talk* condition (*i. e.,* the suppression of sensory consequences following self-initiated actions compared to those following passive external stimulation).

2.5. EEG data acquisition and analysis

A 64-channel EEG system recorded EEG data (BrainVision, Brain Products GmbH). The active electrodes were placed in an elastic cap using the international 10–10 system (FP1, FP2, F7, F8, F3, F4, Fz, FC5, FC6, FC1, FC2, T7, T8, C3, Cz, C4, CP5, CP6, CP1, CP2, TP9, TP10, P7, P8, P3, P4, Pz, O1, O2, Oz, AF7, AF3, AFz, F1, F5, FT7, FC3, FCz, C1, C5, TP7, CP3, P1, P5, PO7, PO3, POz, PO4, PO8, P6, P2, CPz, CP4, TP8, C6, C2, FC4, FT8, F6, F2, AF4, AF8). The impedance did not exceed five kiloohms (kΩ) and the sampling frequency was 500 Hz (Hz). The online reference was the average mastoid ((TP9 + TP10)/2). Data pre-processing was performed with EEGLAB v13.6.5b (Delorme and Makeig, 2004) and Matlab R2022b (MathWorks Inc., MA, USA). A 30-Hz low-pass filter and a 1-Hz high-pass filter were applied. Each continuous EEG recording during the speech condition was visually monitored on a trial-by-trial basis for excessive muscle artifacts at speech onset. Ambiguous speech onsets involving some peaks of anomalous activity were excluded (Ford et al., 2010) via visual inspection of the data by an experienced EEG researcher. Subsequently, eye movements, blinking and any artifacts related to facial muscle activity (especially during the speech condition) were identified and rejected with an Independent Components Analysis (ICA) (Delorme et al., 2007) through manual inspection of the components. EEG data epochs were set from 100 ms before the onset of the auditory stimulus (used for baseline correction) to 350 ms after stimulus onset. Trials that, despite ICA clean-up still contain artifacts (voltages greater than ± 90 ÂµV (µV)) were rejected. During this process, the artifact rejection command indicated the percentage of trials removed from each subject. We considered that if a subject loses more than 70% of the trials, the recording was likely not clean enough; thus, participants with less than 30% of usable trials on average were excluded from the analysis. No significant differences were found in the number of usable trials for each group (Table 1).

N1 ERP was identified as the negative fronto-central peak between 60 and 120 ms after the onset of the phoneme [a:] (Ford et al., 2014, 2010; Mathias et al., 2020), reaching its maximum amplitude at the midline electrodes (Ford et al., 2007a). Based on previous literature that has performed the analysis only on that electrode with maximum N1 suppression (Ford et al., 2007b; Mathalon et al., 2019; Perez et al., 2012; Pinheiro et al., 2020; Whitford et al., 2011), and to minimize the number of statistical tests conducted, the amplitude of FCz within the N1 time window was selected for statistical analysis.

2.6. Statistical analyses

Shapiro-Wilk's normality tests were conducted to check whether the data satisfied the normality requirement. All variables were normally distributed; consequently, parametric tests were chosen for further analysis.

Sociodemographic and cognitive differences between both groups of patients and healthy controls were examined using Chi-squared or paired Student's t-tests for independent samples when corresponding.

The corollary discharge mechanism was analyzed through contrasts between conditions and groups in the suppression of the N1 potential using two sets of analyses. First, to assess N1 differences between conditions, within-group comparisons were performed using a repeated measure 3x2 ANCOVA with *'group'* as the between condition factor (schizophrenia, bipolar, and healthy) and *'task condition'* as within condition factor (*listen/talk* vs *just listen/no talk*) (Fig. 1a, 1b, 1c). Second, to assess between-groups differences in corollary discharge, N1 suppression values (*listen/talk* minus *listen/no talk amplitudes*) were calculated and compared (Fig. 1d) through a one-factor ANCOVA. In both sets of analyses, the effect of treatment (chlorpromazine equivalents in mg/day) was included as a covariate. Effect sizes were assessed using partial eta-squared values and Student's t-tests with Bonferroni correction were computed for post-hoc analyses.

In a second step, linear regression analyses were used separately for both groups of patients to evaluate the relationship between N1 suppression and ASEs intensity as assessed through the IPASE total scores and also its subscales (Cognition, Self-Awareness, Consciousness, Somatization, and Demarcation).

3. Results

There were no significant differences in age, sex, or years of education between people with bipolar disorder or schizophrenia compared to healthy controls. Both groups of participants with diagnosis of bipolar disorder and diagnosis of schizophrenia showed generalized deficits in cognitive scores when compared to healthy controls (Table 1). Fig. 1a, 1b, and 1c show the waveforms of the N1 component in both conditions (i.e., *listen/talk* and *listen/no talk*), while Fig. 1d shows the mean suppression of the N1 component amplitude in the three groups (i.e., both groups of patients and healthy controls). Fig. 2 presents the raincloud plots of the N1 suppression values for each group. Fig. 3 shows the results of the linear regression analyses performed between N1 suppression values and IPASE total scores for both groups of patients.

3.1. ERP amplitude – Within-group comparisons

The repeated measure 3x2 ANCOVA results showed a significant interaction effect between task condition and group (F[1, 85] = 20,112, p = 0.000, ηp^2 = 0.319, statistical power = 1.000). The Student's *t*-test for repeated measures showed significant differences between task conditions (i.e., N1 attenuation effect) in all groups of participants: healthy controls (t = 4.541, p < 0.000; Fig. 1a), bipolar disorder patients (t = 4.121, p < 0.000; Fig. 1b) and schizophrenia patients (t = 3.804, p < 0.001; Fig. 1c), due to, as expected, a lower N1 amplitude in the *listen/talk* compared to the *listen/no talk* condition.

There was no significant interaction effect between task condition and the effect of treatment measured in chlorpromazine equivalents (mg/day) (F[1, 85] = 0.129; p = 0.720).

3.2. ERP amplitude – Between-groups comparisons

The ANCOVA results on the N1 suppression values between groups showed significant differences (F[3, 84] = 5.388, p < 0.002, ηp^2 = 0.160, statistical power = 0.925) (Figure d). The significant results were due to a diminished N1 suppression amplitude in people with schizophrenia when compared to healthy controls (t = 4.259; p = 0.000). In contrast, there were no significant differences in N1 suppression between people with bipolar disorder and healthy controls (t = 1.540; p = 0.250), nor between the two patient groups (t = 2.297; p = 0.103).

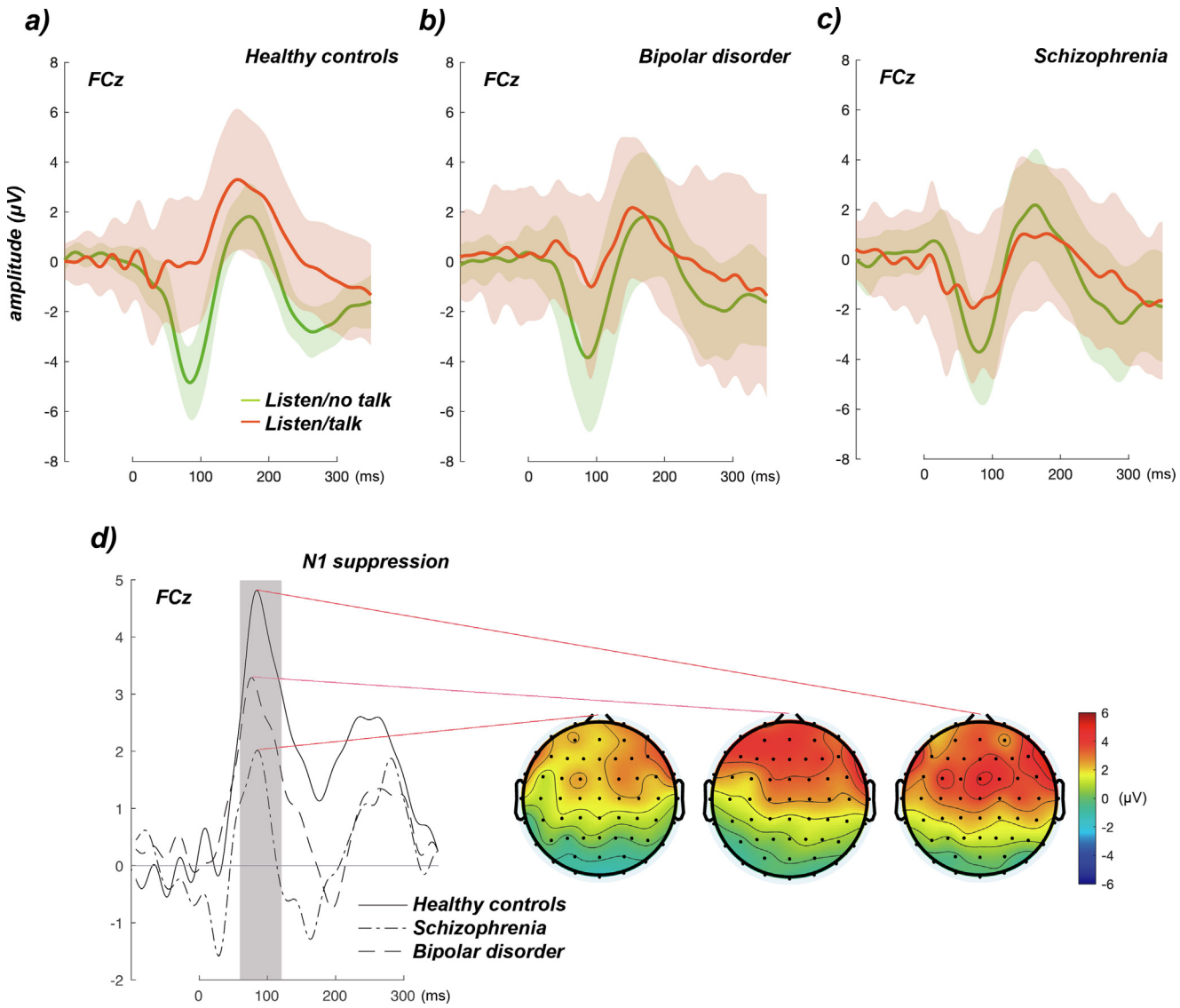

Fig. 1. Averaged evoked waves of FCz in the *listen/talk* (red) and *listen/no talk* (blue) conditions with a 95% confidence interval. The N1 amplitude during the *listen/talk* condition is reduced compared to the *listen/no talk* condition in healthy controls (1a), people with bipolar disorder (1b), and people with schizophrenia (1c). This effect is attenuated in schizophrenia patients, while bipolar patients show an intermediate level of suppression between schizophrenia and control groups (1d). The topographical maps are obtained from the peak of the maximum N1 ERP amplitude in the *listen/talk* condition minus the N1 ERP amplitude in the *listen/no talk* condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

There was no significant effect of the patient's current treatment measured in chlorpromazine equivalents (mg/day) (F[3, 84] = 0.852; p = 0.359).

3.3. ERP correlates of anomalous self-experiences (ASEs)

Regression analyses in patients with schizophrenia showed a significant inverse relationship between N1 suppression values and IPASE total scores (R^2 = 0.300, p = 0.002; blue line in Fig. 3). When analyzing the relationship between the N1 suppression and the IPASE subscales, significant relationships were found for *Self-Awareness and Presence* (R^2 = 0.313, p = 0.001), *Consciousness* (R^2 = 0.255, p = 0.004), *Somatization* (R^2 = 0.329, p = 0.001), and *Demarcation/Transitivism* (R^2 = 0.132, p = 0.049). In contrast, patients with bipolar disorder showed no relationship between N1 suppression and IPASE values in the total scale (Fig. 3; red line) or any of its subscales.

No significant relationship was found between N1 amplitude suppression and antipsychotic doses in people with schizophrenia nor in people with bipolar disorder.

4. Discussion

The primary aim of this study was to evaluate the specificity of the alteration of N1 potential suppression in schizophrenia, associated with the corollary discharge mechanism. To this end, we studied another psychotic clinical population and compared the speech-related suppression of N1 auditory ERP in both groups of patients (with diagnosis of bipolar disorder and schizophrenia), and its relationship with the severity of the ASEs presented in these people.

First, the suppression of the auditory N1 evoked potential during speech compared to passive listening to onés own voice was, as expected, observed in healthy controls (Beño-Ruiz-de-la-Sierra et al, 2023a; Hubl et al., 2014; Wang et al., 2014), and this suppres-

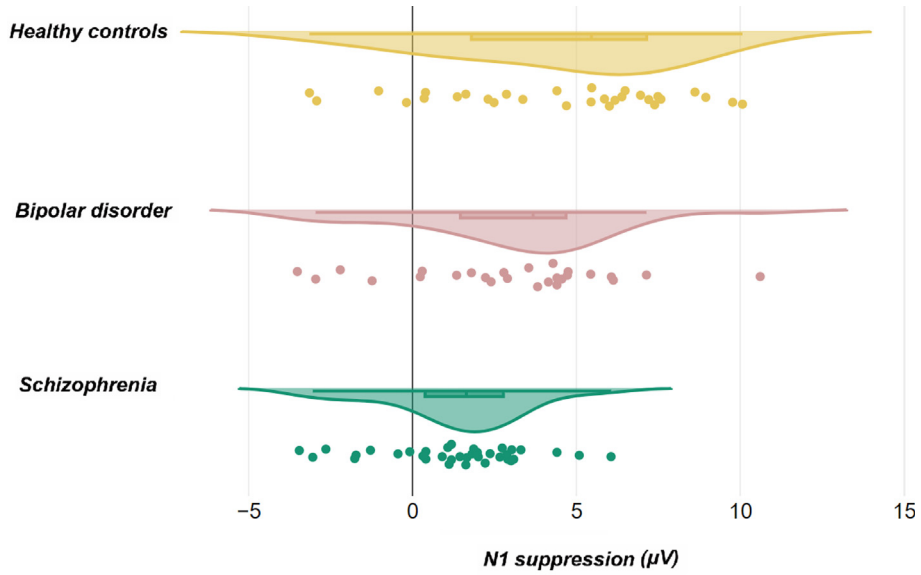

Fig. 2. Distribution of the data, median and interquartile range central tendency, and dispersion of N1 suppression (i.e. *listen/talk* minus *listen/no talk* condition) in healthy controls (yellow), people with bipolar disorder (red) and people with schizophrenia (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

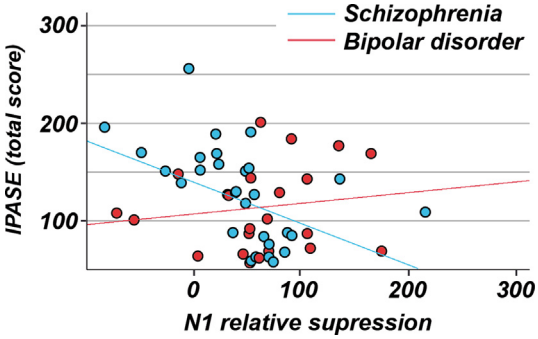

Fig. 3. Significant linear correlations were observed in the regression analyses between N1 suppression and Anomalous Self-Experiences (ASEs) in people with schizophrenia (blue). Smaller N1 suppression during the *listen/talk* condition was associated with higher IPASE total scores. No significant relationship between the two variables was found for people with bipolar disorder (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sion was significantly smaller in participants with schizophrenia, replicating our own and other studies (Beño-Ruiz-de-la-Sierra et al., 2023b; for a review see Whitford, 2019). In the present work we found no significant differences in N1 attenuation values between the groups of bipolar patients and healthy controls. However, the values of patients with bipolar disorder were found to be midway between those of patients with schizophrenia and the control group (Figs. 1 and 2). Additionally, the amount of N1 suppression was significantly related to ASEs severity in the group of patients with schizophrenia, but not in that of bipolar disorder patients (Fig. 3).

The corollary discharge is one of several neurocognitive mechanisms that may play a role in our basic self-experiences (Nelson et al., 2014). This mechanism allows us to identify the source of stimuli by anticipating the sensory effects elicited by an action (Von Holst and Mittelstaedt, 1950; Sperry, 1950). Therefore, it may be involved in the suppression of the N1 auditory potential we found during self-generated speech compared to listening to external stimuli.

Consistent with previous studies (for a review see Whitford, 2019), schizophrenia patients show N1 suppression deficits when listening themselves while uttering their own speech, supporting the theory of an impaired corollary discharge mechanism in these patients (Feinberg, 1978). However, while N1 suppression during the *listen/talk* condition is altered in schizophrenia, both groups of patients (schizophrenia and bipolar disorder) exhibit a normal N1 potential when listening to their own pre-recorded voice (*listen/no talk* condition), indicating that the sensory recognition of their own voice remains intact in these patients. Therefore, the continuum in attenuation shown between the three groups during the *listen/talk* condition are likely attributable to deficits in corollary discharge in schizophrenia.

Different categories of psychotic disorders have been identified, including affective psychoses, where bipolar disorder is considered a spectrum of disorders with blurred boundaries with schizophrenia on one side and unipolar depression on the other, in terms of symptomatology, family history and genetics (Akiskal, 2006; American Psychiatric Association, 2022) and a shared psychotic core (Sorella et al., 2019). Due to the lack of significant differences in N1 suppression between individuals with bipolar disorder and healthy controls, and considering that all patients were in a euthymic state with psychotic features more commonly occurring during manic phases, the altered N1 suppression may be associated with psychosis. Although the impairment in N1 suppression is more pronounced in the schizophrenia group, the fact that we did not find significant differences when comparing both patient groups supports the hypothesis of a link between corollary discharge mechanism alteration and psychotic features, which may manifest in a smaller subset of bipolar patients compared to those with schizophrenia.

The significant relationship between the deficit in sensorimotor attenuation (N1 component) and ASEs is only shown in the schizophrenia group. Considering that our data support a clear dysfunction of this mechanism in schizophrenia but not in bipolar disorder, this suggests that ASEs in bipolar disorder, when present, would not relate to corollary discharge alterations. This neural mechanism serves as crucial for recognizing the source of actions as self-generated, thus playing a vital role in self-identification. Consequently, its dysfunction is likely to represent a neural signature of altered ipseity, more evident or marked in schizophrenia than in bipolar disorder. The reduced N1 suppression observed

in people with schizophrenia suggests that the neural processing associated with mental contents linked to the subject's actions resembles that of sensory stimulation from an external source. Therefore, this could pose greater challenges for schizophrenia than for bipolar patients in discerning the origin of mental contents, a difficulty that aligns closely with the features of ASEs and might exacerbate the diminished sense of self (ipseity) observed in schizophrenia.

During vocalization, the corollary discharge mechanism is thought to be engaged via an inhibitory feed-forward process, where parvalbumin interneurons within the auditory cortex inhibit pyramidal neurons (Eliades and Wang, 2008; Nelson et al., 2013; Reznik and Mukamel, 2019; Schneider et al., 2014). This process may involve synchronization mediated by inhibitory transmission between the motor efferent area and the sensory region receiving the related signal (Chen et al., 2011; Ford et al., 2005, 2002). Taking this into account, the deficit in the corollary discharge mechanism shown in our patients with schizophrenia, appears consistent with an overactive cortex, which is in line with reported GABA deficits in the cortex in schizophrenia (Lewis et al., 2005). Such deficits are less evident in bipolar disorder, with a smaller proportion of cases showing inhibitory deficits (Volk et al., 2016) which would be coherent in this framework with the smaller suppression of corollary discharge in the latter group in our study. In this context, if corollary discharge mechanisms are based on cortical inhibition, the intermediate suppression values of bipolar patients between schizophrenia and healthy control participants could speculatively relate to the presence of a cortical inhibitory deficit in a smaller subset of bipolar as compared to schizophrenia patients.

Besides, corollary discharge malfunction has been proposed to relate to abnormal frontal white-matter myelination in schizophrenia (Whitford et al., 2012), and the level of N1-suppression has been related to the structural integrity of the arcuate fasciculus in these patients (Whitford et al., 2017). Reduced intracortical myelin has been found in both schizophrenia and bipolar disorder (Jørgensen et al., 2016), but myelination characteristics may differ between these syndromes (Hercher et al., 2014). Therefore, higher severity of alterations in myelination in schizophrenia, while still present in bipolar disorder, may explain the intermediate suppression of N1 in the latter group.

Diverse motor abnormalities are notably prevalent during the clinical phases of schizophrenia. However, those primarily rely on sensorimotor integration facilitated by corollary discharge mechanisms appear relatively early during developmental years (Burton et al., 2016; Hirjak et al., 2018; Poletti et al., 2019). This suggests that alteration in this mechanism may occur early in neurodevelopment, potentially heightening the risk of subsequent psychotic conditions (Poletti et al., 2019), and thus affecting the development of an intact sense of self.

Among the limitations of our study, we did not incorporate a treatment-naïve sample and thus an effect of treatment cannot be completely ruled out. However, we did not find a significant relation between N1 suppression and pharmacological dose. Secondly, the sample size of bipolar participants is smaller than for schizophrenia, but the relation between auditory corollary discharge and ASEs has not been previously tested in the former group. However, a larger sample is necessary to confirm these results. We used the IPASE for assessing ASEs instead of the gold-standard EASE. Nevertheless, scores from both instruments exhibit a high correlation (Nelson et al., 2019), and a researcher was present to assist participants in case of any misunderstanding of item phrasing. Although corollary discharge is likely to underpin the ipseity experience, we cannot infer a causal relationship for two reasons: i) our results are correlational between measures of ASEs and N1 auditory ERP suppression, and ii) this suppression effect may be just one of the multiple possible measures of the corollary discharge mechanism.

The potential cofound of stimulus novelty in the *listen/no talk* condition should not account for the results found, as no significant differences have been found in healthy controls when comparing the N1 ERP generated by passively listening to their own recorded voice versus listening to another person's voice (Beño-Ruiz-de-la-Sierra et al., 2023a; Heinks-maldonado et al., 2005). Nevertheless, implementing a third condition where both groups of patients passively listen to an unfamiliar voice in future research could be beneficial for evaluate this in people with psychosis. Additionally, testing bipolar participants in their manic phase, when they show psychotic features, would help determine whether N1 suppression is related to the psychotic state or if it is specific to schizophrenia.

5. Conclusions

The dysfunction of the corollary discharge mechanism may characterize schizophrenia, where it relates to ASEs. This altered mechanism is less evident in bipolar patients, while no relationship with ASEs could be found.

CRediT authorship contribution statement

Rosa M. Beño-Ruiz-de-la-Sierra: Conceptualization, Methodology, Formal analysis, Validation, Investigation, Writing – original draft. **Antonio Arjona-Valladares:** Conceptualization, Methodology, Formal analysis, Validation, Investigation, Writing – original draft. **Marta Hernández-García:** Investigation, Resources, Writing – review & editing. **Inés Fernández-Linsenbarth:** Investigation, Validation, Writing – review & editing. **Álvaro Díez:** Formal analysis, Writing – review & editing. **Alejandro Roig-Herrero:** Investigation, Writing – review & editing. **Emma Osorio-Iriarte:** Investigation, Writing – review & editing. **Vicente Molina:** Conceptualization, Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Acknowledgements

This work was supported by the following grants: 'Instituto de Salud Carlos III' (ID PI22/00465), 'Gerencia Regional de Salud de Castilla y León' (IDs , GRS 2487/A/22 and GRS 2685/A/2023), 'Fundació La Marató' (ID 571/C/2022), predoctoral grant 'Consejería de Educación, Junta de Castilla y León' (Spain) and European Social Fund (ID VA-223-19 to RMBR), and 'Programa INVESTIGO' European Union NextGenerationEU (to EOI). Funding sources had no other role than financial support providers.

We appreciate the collaboration of all the participants in our research, who gave their precious time and allowed their data to be used in this study.

Conflict of interest statement

None of the authors have potential conflicts of interest to disclosed.

References

Akiskal H. Trastornos bipolares: conceptos clínicos, neurobiológicos y terapéuticos. Editoral M. 2006.

American Psychiatric Association. Diagnostic and statistical manual of mental disorders. Fifth Edition Text Revision. Amerian Ps. Washington, DC: 2022.

Beño-Ruiz-de-la-Sierra RM, Arjona-Valladares A, Fondevila Estevez S, Fernández-Linsenbarth I, Díez Á, Molina V. Corollary discharge function in healthy controls : Evidence about self-speech and external speech processing. Eur J Neurosci 2023:1–9. https://doi.org/10.1111/ejn.16125.

Beño-Ruiz-de-la-Sierra RM, Arjona-Valladares A, Hernández-García M, Fernández-Linsenbarth I, Díez Á, Fondevila Estevez S, et al. Corollary discharge dysfunction as a possible substrate of anomalous self-experiences in schizophrenia. Schizophr Bull 2023:1–10. https://doi.org/10.1093/schbul/sbad157.

Burton BK, Hjorthøj C, Jepsen JR, Thorup A, Nordentoft M, Plessen KJ. Research review: Do motor deficits during development represent an endophenotype for schizophrenia ? A meta-analysis 2016;4:446–56. https://doi.org/10.1111/jcpp.12479.

Chelune GJ, Baer RA. Journal of clinical and experimental neuropsychology developmental norms for the wisconsin card sorting test. J Clin Exp Neuropsychol 1986;8:219–28.

Chen C-M-A, Mathalon DH, Roach BJ, Cavus I, Spencer DD, Ford JM. The corollary discharge in humans is related to synchronous neural oscillations. J Cogn Neurosci 2011;23:2892–904. https://doi.org/10.1162/jocn.2010.21589.The.

Cicero DC, Neis AM, Klaunig MJ, Trask CL. The inventory of psychotic-like anomalous self-experiences (IPASE): Development and validation. Psychol Assess 2017;29:13–25. https://doi.org/10.1037/pas0000304.

Delorme A, Makeig S. EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J Neurosci Methods 2004;134:9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.

Delorme A, Sejnowski T, Makeig S. Enhanced detection of artifacts in EEG data using higher-order statistics and independent component analysis. Neuroimage 2007;34:1443–9. https://doi.org/10.1016/j.neuroimage.2006.11.004.

Durá IF, Peris MR, Dasí C, Carlos J, Ruiz R. Versión abreviada del WAIS-III para su uso en la evaluación de pacientes con diagnóstico de esquizofrenia. Psicothema 2010;22:202–7.

Ebisch SJH, Mantini D, Northoff G, Salone A, De Berardis D, Ferri F, et al. Altered brain long-range functional interactions underlying the link between aberrant self-experience and self-other relationship in first-episode schizophrenia. Schizophr Bull 2014;40:1072–82. https://doi.org/10.1093/schbul/sbt153.

Eliades SJ, Wang X. Neural substrates of vocalization feedback monitoring in primate auditory cortex. Nature 2008;453:1102–6. https://doi.org/10.1038/nature06910.

Feinberg I. Efference copy and corollary discharge : implications for thinking and its disorders. Schizophr Bull 1978;4:636–40.

Ford JM, Gray M, Faustman WO, Heinks TH, Mathalon DH. Reduced gamma-band coherence to distorted feedback during speech when what you say is not what you hear. Int J Psychophysiol 2005;57:143–50. https://doi.org/10.1016/j.ijpsycho.2005.03.002.

Ford JM, Gray M, Faustman WO, Roach BJ, Mathalon DH. Dissecting corollary discharge dysfunction in schizophrenia. Psychophysiology 2007a;44:522–9. https://doi.org/10.1111/j.1469-8986.2007.00533.x.

Ford JM, Mathalon DH, Roach BJ, Keedy SK, Reilly JL, Gershon ES, et al. Neurophysiological evidence of corollary discharge function during vocalization in psychotic patients and their nonpsychotic first-degree relatives. Schizophr Bull 2013;39:1272–80. https://doi.org/10.1093/schbul/sbs129.

Ford JM, Mathalon DH, Whitfield S, Faustman WO, Roth WT. Reduced communication between frontal and temporal lobes during talking in schizophrenia. Biol Psychiatry 2002;51:485–92. https://doi.org/10.1016/S0006-3223(01)01335-X.

Ford JM, Palzes VA, Roach BJ, Mathalon DH. Did i do that? Abnormal predictive processes in schizophrenia when button pressing to deliver a tone. Schizophr Bull 2014;40:804–12. https://doi.org/10.1093/schbul/sbt072.

Ford JM, Roach BJ, Faustman WO, Mathalon DH. Synch before you speak: Auditory hallucinations in schizophrenia. Am J Psychiatry 2007b;164:458. https://doi.org/10.1176/appi.ajp.164.3.458.

Ford JM, Roach BJ, Mathalon DH. Assessing corollary discharge in humans using noninvasive neurophysiological methods. Nat Protoc 2010;5:1160–8. https://doi.org/10.1038/nprot.2010.67.

Haug E, Oie M, Andreassen OA, Bratlien U, Raballo A, Nelson B, et al. Anomalous self-experiences contribute independently to social dysfunction in the early phases of schizophrenia and psychotic bipolar disorder. Compr Psychiatry 2014;55:475–82. https://doi.org/10.1016/j.comppsych.2013.11.010.

Heinks-maldonado TH, Mathalon DH, Gray MAX. Fine-tuning of auditory cortex during speech production 2005;42:180–90. doi: 10.1111/j.1469-8986.2005.00272.x.

Heinks-maldonado TH, Mathalon DH, Houde JF, Gray M, Faustman WO, Ford JM. Relationship of Imprecise Corollary Discharge in Schizophrenia to Auditory Hallucinations 2007;64.

Hercher C, Chopra V, Beasley CL. Evidence for morphological alterations in prefrontal white matter glia in schizophrenia and bipolar disorder. J Psychiatry Neurosci 2014;39:376–85. https://doi.org/10.1503/jpn.130277.

Hernández-García M, Gómez-García M, Sotelo E, Fernández-Linsenbarth I, Andrés-Olivera P, de Alarcon-Gómez R, et al. Anomalous self-experiences are related to general cognition deficits in schizophrenia. Eur Arch Psychiatry Clin Neurosci 2021;271:707–12. https://doi.org/10.1007/s00406-020-01213-z.

Hirjak D, Meyer-lindenberg A, Kubera KM, Thomann PA, Wolf RC. Neuroscience and Biobehavioral Reviews Motor dysfunction as research domain in the period preceding manifest schizophrenia : A systematic review. Neurosci Biobehav Rev 2018;87:87–105. https://doi.org/10.1016/j.neubiorev.2018.01.011.

Von Holst E, Mittelstaedt H. Das reafferenzprinzip: wechselwirkungen zwischen zentralnervensystem und peripherie. Naturwissenschaften 1950;37(20):464–76.

Hubl D, Schneider RC, Kottlow M, Kindler J, Strik W, Dierks T, et al. Agency and Ownership are Independent Components of ' Sensing the Self ' in the Auditory-Verbal Domain. Brain Topogr 2014:672–82. https://doi.org/10.1007/s10548-014-0351-0.

Jørgensen KN, Nerland S, Norbom LB, Doan NT, Nesvåg R, Mørch-Johnsen L, et al. Increased MRI-based cortical grey/white-matter contrast in sensory and motor regions in schizophrenia and bipolar disorder. Psychol Med 2016;46:1971–85. https://doi.org/10.1017/S0033291716000593.

Kay SR, Fiszbein A, Opler LA. The positive and negative syndrome scale (PANSS) for schizophrenia. Schizophr Bull 1987;13:261–76. https://doi.org/10.1093/schbul/13.2.261.

Keefe RSE, Harvey PD, Goldberg TE, Gold JM, Walker TM, Kennel C, et al. Norms and standardization of the Brief Assessment of Cognition in Schizophrenia (BACS). Schizophr Res 2008;102:108–15. https://doi.org/10.1016/j.schres.2008.03.024.

Kirkpatrick B, Strauss GP, Nguyen L, Fischer BA, Daniel DG, Cienfuegos A, et al. The brief negative symptom scale: Psychometric properties. Schizophr Bull 2011;37:300–5. https://doi.org/10.1093/schbul/sbq059.

Lewis DA, Hashimoto T, Volk DW. Cortical inhibitory neurons and schizophrenia. Nat Rev Neurosci 2005;6:312–24. https://doi.org/10.1038/nrn1648.

Madeira L, Bonoldi I, Rocchetti M, Samson C, Azis M, Queen B, et al. An initial investigation of abnormal bodily phenomena in subjects at ultra high risk for psychosis: Their prevalence and clinical implications. Compr Psychiatry 2016;66:39–45. https://doi.org/10.1016/j.comppsych.2015.12.005.

Mathalon DH, Roach BJ, Ferri JM, Loewy RL, Stuart BK, Perez VB, et al. Deficient auditory predictive coding during vocalization in the psychosis risk syndrome and in early illness schizophrenia: The final expanded sample. Psychol Med 2019;49:1897–904. https://doi.org/10.1017/S0033291718002659.

Mathias B, Zamm A, Gianferrara PG, Ross B, Palmer C. Rhythm complexity modulates behavioral and neural dynamics during auditory–motor synchronization. J Cogn Neurosci 2020;32:1864–80. https://doi.org/10.1162/jocn_a_01601.

Nelson A, Schneider DM, Takatoh J, Sakurai K, Wang F, Mooney R. A circuit for motor cortical modulation of auditory cortical activity. J Neurosci 2013;33:14342–53. https://doi.org/10.1523/JNEUROSCI.2275-13.2013.

Nelson B, Lavoie S, Gawęda LE, Sass LA, Koren D, et al. The neurophenomenology of early psychosis: An integrative empirical study. Conscious Cogn 2020;77. https://doi.org/10.1016/j.concog.2019.102845.

Nelson B, Li E, Cicero DC, Gawęda Ł, Hartmann JA, Koren D, et al. The construct validity of the inventory of psychotic-like anomalous self-experiences (IPASE) as a measure of minimal self-disturbance: Preliminary data. Early Interv Psychiatry 2019;13:686–91. https://doi.org/10.1111/eip.12711.

Nelson B, Whitford TJ, Lavoie S, Sass LA. What are the neurocognitive correlates of basic self-disturbance in schizophrenia?: Integrating phenomenology and neurocognition. Part 1 (Source monitoring deficits). Schizophr Res 2014;152:12–9. doi: 10.1016/j.schres.2013.06.022.

Nordgaard J, Nilsson LS, Sæbye D, Parnas J. Self-disorders in schizophrenia-spectrum disorders: a 5-year follow-up study. Eur Arch Psychiatry Clin Neurosci 2018;268:713–8. https://doi.org/10.1007/s00406-017-0837-3.

Perez VB, Ford JM, Roach BJ, Loewy RL, Stuart BK, Vinogradov S, et al. Auditory cortex responsiveness during talking and listening: Early illness schizophrenia and patients at clinical high-risk for psychosis. Schizophr Bull 2012;38:1216–24. https://doi.org/10.1093/schbul/sbr124.

Pinheiro AP, Schwartze M, Gutiérrez-Domínguez F, Kotz SA. Real and imagined sensory feedback have comparable effects on action anticipation. Cortex 2020;130:290–301. https://doi.org/10.1016/j.cortex.2020.04.030.

Poletti M, Tortorella A, Raballo A. Review impaired corollary discharge in psychosis and at-risk states : Integrating neurodevelopmental, phenomenological, and clinical perspectives. Biol Psychiatry Cogn Neurosci Neuroimaging 2019:1–10. https://doi.org/10.1016/j.bpsc.2019.05.008.

Raballo A, Parnas J. Examination of anomalous self-experience: Initial study of the structure of self-disorders in schizophrenia spectrum. J Nerv Ment Dis 2012;200:577–83. https://doi.org/10.1097/NMD.0b013e31825bfb41.

Raballo A, Sæbye D, Parnas J. Looking at the schizophrenia spectrum through the prism of self-disorders: An empirical study. Schizophr Bull 2011;37:344–51. https://doi.org/10.1093/schbul/sbp056.

Reznik D, Mukamel R. Motor output, neural states and auditory perception. Neurosci Biobehav Rev 2019;96:116–26. https://doi.org/10.1016/j.neubiorev.2018.10.021.

Roig-Herrero A, Planchuelo-Gómez Á, Hernández-García M, de Luis-García R, Fernández-Linsenbarth I, Beño-Ruiz-de-la-Sierra RM, et al. Default mode network components and its relationship with anomalous self-experiences in schizophrenia: A rs-fMRI exploratory study. Psychiatry Res - Neuroimaging 2022;324. https://doi.org/10.1016/j.pscychresns.2022.111495.

Sass LA, Parnas J. Schizophrenia, Consciousness, and the Self 2003:427–44.

Schneider DM, Nelson A, Mooney R. A synaptic and circuit basis for corollary discharge in the auditory cortex. Nature 2014;513:189–94. https://doi.org/10.1038/nature13724.

Segarra N, Bernardo M, Gutierrez F, Justicia A, Fernadez-egea E, Allas M. Spanish validation of the Brief Assessment in Cognition in Schizophrenia (BACS) in patients with schizophrenia and healthy controls. Eur Psychiatry 2011;26:69–73. https://doi.org/10.1016/j.eurpsy.2009.11.001.

Sorella S, Lapomarda G, Messina I, Frederickson JJ, Siugzdaite R, Job R, et al. Testing the expanded continuum hypothesis of schizophrenia and bipolar disorder. Neural and psychological evidence for shared and distinct mechanisms. NeuroImage Clin 2019;23. https://doi.org/10.1016/j.nicl.2019.101854 101854.

Sperry RW. Neural basis of the spontaneous optokinetic response produced by visual inversion. J Comp Physiol Psychol 1950;43:482–9. https://doi.org/10.1037/h0055479.

Volk DW, Sampson AR, Zhang Y, Edelson JR, Lewis DA. Cortical GABA markers identify a molecular subtype of psychotic and bipolar disorders. Psychol Med 2016;46:2501–12. https://doi.org/10.1017/S0033291716001446.

Wang J, Mathalon DH, Roach BJ, Reilly J, Keedy SK, Sweeney JA, et al. Action planning and predictive coding when speaking. Neuroimage 2014;91:91–8. https://doi.org/10.1016/j.neuroimage.2014.01.003.

Wechsler D. Wechsler Adult Intelligence, and Third Edition Administration and Scoring Manual. San Antonio, TX Psychol Corp 1997:217.

Whitford TJ. Review speaking-induced suppression of the auditory cortex in humans and its relevance to schizophrenia. Biol Psychiatry Cogn Neurosci Neuroimaging 2019;4:791–804. https://doi.org/10.1016/j.bpsc.2019.05.011.

Whitford TJ, Ford JM, Mathalon DH, Kubicki M, Shenton ME. Schizophrenia, myelination, and delayed corollary discharges: A hypothesis. Schizophr Bull 2012;38:486–94. https://doi.org/10.1093/schbul/sbq105.

Whitford TJ, Jack BN, Pearson D, Griffiths O, Luque D, Harris AWF, et al. Neurophysiological evidence of efference copies to inner speech. Elife 2017:1–23. https://doi.org/10.7554/eLife.28197.001.

Whitford TJ, Mathalon DH, Shenton ME, Roach BJ, Bammer R, Adcock RA, et al. Electrophysiological and diffusion tensor imaging evidence of delayed corollary discharges in patients with schizophrenia. Psychol Med 2011;41:959–69. https://doi.org/10.1017/S0033291710001376.

Yao B, Rolfs M, Slate R, Roberts D, Fattal J, Achtyes ED, et al. Abnormal Oculomotor Corollary Discharge Signaling as a Trans-diagnostic Mechanism of Psychosis 2024;50:631–41.