Beyond the Broken Error-Related Negativity: Functional and Diagnostic Correlates of Error Processing in Psychosis

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Background: Studies of event-related potentials have consistently shown that schizophrenia is associated with a blunted error-related negativity (ERN), indicating a deficit in error monitoring. It is unknown whether this deficit is unique to schizophrenia or is common to psychotic disorders more broadly, and its associations with clinical characteristics of the illness are not well understood.

Methods: The ERN and the error positivity (Pe) were recorded from 33 individuals with schizophrenia, 45 individuals with other psychotic disorders, and 33 healthy control subjects. Patients were drawn from a cohort with psychotic disorders followed since first hospitalization and diagnosed by consensus based on 10 years of observation.

Results: The ERN was profoundly blunted in the patient group, regardless of diagnosis, indicating that this deficit is not unique to schizophrenia. The Pe, meanwhile, was blunted only among individuals with schizophrenia, indicating that the ERN and Pe are differentially related to psychotic illnesses. A blunted ERN was associated with more severe negative symptoms and poorer real-world functioning, as indicated by unemployment and re-hospitalization over 10 years of illness. Although reduced compared with control subjects, ERN amplitude was greater in patients with higher neuroticism, indicating that error processing is moderated by personality differences in the same manner as in healthy populations.

Conclusions: The current study advances the literature by evaluating diagnostic specificity and functional correlates of impaired error processing in psychosis.

Key Words: EEG, ERN, ERP, error positivity, psychosis, schizophrenia

For decades, event-related potentials (ERPs) have been used to shed light on the pathophysiology of schizophrenia across a range of cognitive domains, identifying abnormal neural activity associated with stimulus processing, selective attention, working memory, and semantic processing (1). With regard to executive function, ERP studies in schizophrenia have observed blunted neural activity associated with action monitoring on speeded reaction-time tasks. These studies have focused on the error-related negativity (ERN), a response that peaks within the first 100 msec following error commission. Converging ERP and neuroimaging evidence indicates that the ERN is generated within the anterior cingulate cortex (ACC) (2), and it is thought to reflect the dopaminergic disinhibition of ACC neurons when errors occur (3). In schizophrenia, the ERN has been consistently shown to be blunted across a range of tasks (4–9) and has been associated with worse performance on behavioral measures of executive function (10). A reduced ERN reflects impaired error detection, and it is consistent with the existing neuroimaging literature showing reduced ACC activity in schizophrenia during error processing (11,12). This is in contrast to other psychiatric conditions, particularly anxiety disorders, in which the ERN is increased (13). More broadly, an enhanced ERN has also been found among individuals high in neuroticism (14,15), although the influence of personality traits on the ERN has not been examined in schizophrenia.

While reduction of the ERN in schizophrenia is well documented, several important questions remain. First, the specificity of this finding is unknown—extant studies have not compared schizophrenia with other psychotic disorders; it is possible that a blunted ERN is reflective of psychosis more generally. This is challenging to study because in cross-sectional assessments, patients with schizophrenia are frequently misdiagnosed as having other psychotic disorders, especially during the early course of the illness (16–18). We aimed to address this gap by examining a cohort of patients whose psychotic diagnoses were formulated based on a decade of observation. In light of neuropsychological findings that impairment is more severe in schizophrenia than in other psychotic disorders (19,20), we hypothesized that ERN amplitude would be blunted among individuals with schizophrenia compared with those with other psychotic disorders. Second, although deficits on behavioral measures of executive function have been linked to negative symptom severity and real-world impairment (21–23), the relations between these variables and the ERN are unclear. We hypothesized that, as with behavioral measures of executive function, blunted ERN amplitude would be linked to negative symptom severity, occupational status, and frequency of hospitalization. Conversely, we predicted that ERN amplitude would be increased among patients with high neuroticism, as has been observed in other populations (14,15).

Third, studies in schizophrenia to date have indicated a reduced ERN, while differences in a related ERP component, the error positivity (Pe), have not been observed. The Pe is a positive slow wave that peaks later than the ERN, at approximately 200 msec to 400 msec (24). Whereas the ERN has been related to automatic error detection, the Pe has been related to conscious error recognition and response adjustment following error commission (25,26). Prior studies in schizophrenia have generally not found group differences in Pe amplitude, suggesting that this ERP component is intact (7–10). This is surprising given the similarity of the Pe to the P300, another positive slow wave that is elicited by task-relevant stimuli

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Table 1. Sample Characteristics

	Schizophrenia Spectrum ($n = 33$)		Other Psychosis ($n = 45$)		Control Subjects ($n = 33$)		
	n	%	*n*	%	*n*	%	Group Comparison
Gender							
Male	24	72.7	29	64.4	22	66.7	$\chi^2(2) = .61$
Female	9	27.3	16	35.6	11	33.3	
Ethnicity							
Caucasian	26	78.8	36	80.0	23	69.7	$\chi^2(2) = 1.26$
Other	7	21.2	9	20.0	10	30.3	
Socioeconomic Status							
Blue collar or below	14	42.4	20	44.4			$\chi^2(1) = .03$
White collar	19	57.6	25	55.6			
Medication							
Antipsychotic	27	81.8	10	22.2			$\chi^2(1) = 27.12^a$
Antidepressant	12	36.3	14	31.1			$\chi^2(1) = .24$
Mood stabilizer	10	30.3	10	22.2			$\chi^2(1) = .65$
Benzodiazepine	4	12.1	7	15.6			$\chi^2(1) = .19$
Rehospitalizations, Year 0–4							
None or one	24	72.7	34	75.6			$\chi^2(1) = .08$
Two or more	9	27.3	11	24.4			
Rehospitalizations, Year 5–10							
None or one	21	63.6	34	77.3			$\chi^2(1) = 1.72$
Two or more	12	36.3	10	22.7			
Occupational Status							
Employed	14	42.4	36	80.0			$\chi^2(1) = 12.85^a$
Unemployed	19	57.6	8	17.8			
Social Functioning							
Not impaired	7	21.2	33	75.0			$\chi^2(1) = 21.86^a$
Impaired	26	78.8	11	25.0			
	Mean	SD	Mean	SD	Mean	SD	
Age	44.0	7.8	43.3	9.6	43.8	12.8	$F(2,108) = .05$
Symptoms—Total Scores							
Negative	18.2	12.0	6.8	9.8			$t(76) = 4.59^a$
Psychotic	4.1	7.4	.9	3.6			$t(76) = 2.48^b$
Disorganized	2.7	4.4	1.6	3.0			$t(76) = 1.37$
Antipsychotic Dosage (mg)	582.3	451.2	495.9	550.1			$t(30) = .46$
Neuroticism	15.5	7.5	16.2	6.8			$t(75) = .47$
Premorbid IQ (WRAT3 Score)	46.3	5.9	48.1	4.8			$t(75) = 1.67$

Antipsychotic dosage is the chlorpromazine equivalent computed for participants prescribed antipsychotics.
SD, standard deviation; WRAT3, Wide Range Achievement Test, 3rd Edition.
[a] $p < .001$.
[b] $p < .05$.

(27). It has been suggested that the Pe is a P300 response to the internal detection of errors (28), and a blunted P300 is one of the most reliable neural markers of schizophrenia (29,30). One possibility is that prior studies have lacked statistical power to detect Pe differences, with patient samples ranging from 12 to 18 participants. Another possibility is the Pe was attenuated during data processing, with some studies using relatively conservative high-pass filters (1–2 Hz), which might filter out the component altogether and obscure potential group differences (8,10). We examined whether Pe differences would be apparent with a larger patient sample and a broader filter that would retain slow wave activity in the waveform. While the Pe has yet to be examined in other psychotic disorders, prior work has suggested that the P300 may be differentially reduced in schizophrenia compared with affective psychosis (31,32), and we examined whether diagnostic effects would also be apparent for the Pe.

Methods and Materials

Participants

Data were collected from 104 individuals with a history of psychosis: 48 with a schizophrenia spectrum diagnosis (SZ; schizophrenia, schizoaffective disorder) and 56 with other psychotic disorders (OP; psychotic mood disorder, substance induced, not otherwise specified). The sample was drawn from the Suffolk County Mental Health Project (16,33), an epidemiologic longitudinal study of first-admission psychosis. Participants were recruited from the 12 inpatient psychiatric facilities of Suffolk County, New York, between 1989 and 1995; eligibility criteria included the presence of psychosis, age 15 to 60 at admission, and ability to provide informed consent. Longitudinal consensus DSM-IV diagnoses were made by psychiatrist teams following the 10-year assessment based on information from clinical interviews, medical records, and significant

Table 2. Flankers Task Performance

	Schizophrenia		Other Psychosis		Control Subjects		
	Mean	SD	Mean	SD	Mean	SD	Group Comparison
% Correct Trials	92.5	5.3	93.4	4.5	91.7	4.9	$F(2,108) = 1.75$
Incompatible Errors	17.7	13.7	15.3	9.9	21.6	12.6	$F(2,108) = 2.68$
Compatible Errors	6.4	5.6	5.3	5.7	7.0	7.2	$F(2,108) = .77$
Reaction Time (msec)							
Error trials	430.3	136.6	404.7	108.9	361.8	67.3	$F(2,108) = 10.39^a$
Correct after correct	560.3	111.4	509.4	97.6	452.7	92.2	$F(2,108) = 9.51^a$
Correct after error	612.3	162.6	557.5	128.0	474.4	105.0	$F(2,108) = 8.98^a$
Posterror slowing	52.0	81.1	48.0	61.7	21.7	56.7	$F(2,108) = 2.07$
Correct compatible	535.1	113.5	486.0	99.0	423.9	88.1	$F(2,108) = 10.14^a$
Correct incompatible	609.9	114.4	553.5	114.1	490.8	96.5	$F(2,108) = 9.81^a$
Incompatible slowing	74.8	41.6	67.5	28.5	67.0	31.9	$F(2,108) = .58$

Posterror slowing calculated as the difference between correct trials after errors and correct trials after correct trials. Incompatible slowing calculated as the difference between incompatible and compatible correct trials.

SD, standard deviation.

$^a p < .01$.

others (18,34). Prior work with this cohort indicates that schizophrenia and schizoaffective disorder are characterized by more severe symptoms and cognitive impairment than other psychotic disorders (20), leading us to combine them into the SZ group.

The present assessment was conducted approximately 15 years after the first admission (range: 12.4–19.1 years). Twenty-six participants were excluded either because of poor task performance (fewer than 75% correct trials; 7 SZ, 2 OP), because the quality of ERP data was poor (fewer than 50% artifact-free trials; 3 SZ, 6OP), for having zero artifact-free error trials (4 SZ, 3 OP), or for declining to complete the clinical interview (1 SZ). The final clinical sample consisted of 78 individuals (33 SZ, 45 OP).

As part of a larger study on error-related brain activity, 33 control subjects with no history of any Axis I diagnosis, no current psychiatric medication usage, and no history of neurological illness were recruited from the community; the control group was matched to the patient groups on age, gender, and ethnicity. Eligibility was ascertained using the Structured Clinical Interview for DSM-IV Disorders (SCID) (35), administered by master's-level clinicians. Data from a subgroup of control subjects were presented in a prior report on generalized anxiety disorder (36). This study was formally approved by the Institutional Review Board at Stony Brook University, including the integration of the current data with the patients' historical data.

Task and Materials

Contemporaneous Measures. Symptoms of psychosis in the month preceding the electroencephalogram (EEG) assessment were rated using the Scale for the Assessment of Positive Symptoms (37) and the Scale for the Assessment of Negative Symptoms (38). Ratings were made by two master's-level interviewers, and the reliability was excellent (average intraclass $r = .83$). Based on the results of prior factor analysis (39), the Scale for the Assessment of Negative Symptoms was scored as a single index and the Scale for the Assessment of Positive Symptoms as two symptom subscales: psychotic (hallucinations, delusions) and disorganized (bizarre behavior, thought disorder). Symptom information was obtained using the SCID (40). Medication status variables were defined categorically (using vs. not using in the preceding month) for four target drug classes: antipsychotics, antidepressants, mood stabilizers, and benzodiazepines. Chlorpromazine equivalent dosage was also calculated using power law formulas (41); five patients had missing dosage data. Personality traits were assessed with the 44-item Big Five Inventory, a measure of the five general dimensions of person-

Table 3. Within-Subjects ERP Comparisons: Error Versus Correct Trials

	ERN				Pe			
	Error		Correct		Error		Correct	
Group	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Control Subjects	1.45	6.32	8.10	5.74	9.16	6.55	2.43	3.65
Other Psychosis	2.53	4.43	3.83	3.46	8.32	5.96	.71	2.53
Schizophrenia	1.86	5.43	1.55	4.39	2.36	5.91	−.62	3.63
	Comparison		Partial η^2		Comparison		Partial η^2	
Control Subjects	$t(32) = 6.31^a$		.56		$t(32) = 6.68^a$		.58	
Other Psychosis	$t(44) = 2.34^b$		.11		$t(44) = 8.47^a$		.62	
Schizophrenia	$t(32) = .32$		.01		$t(32) = 3.72^a$		.30	

ERN, error-related negativity; ERP, event-related potential; Pe, error positivity; SD, standard deviation.

$^a p < .001$.

$^b p < .05$.

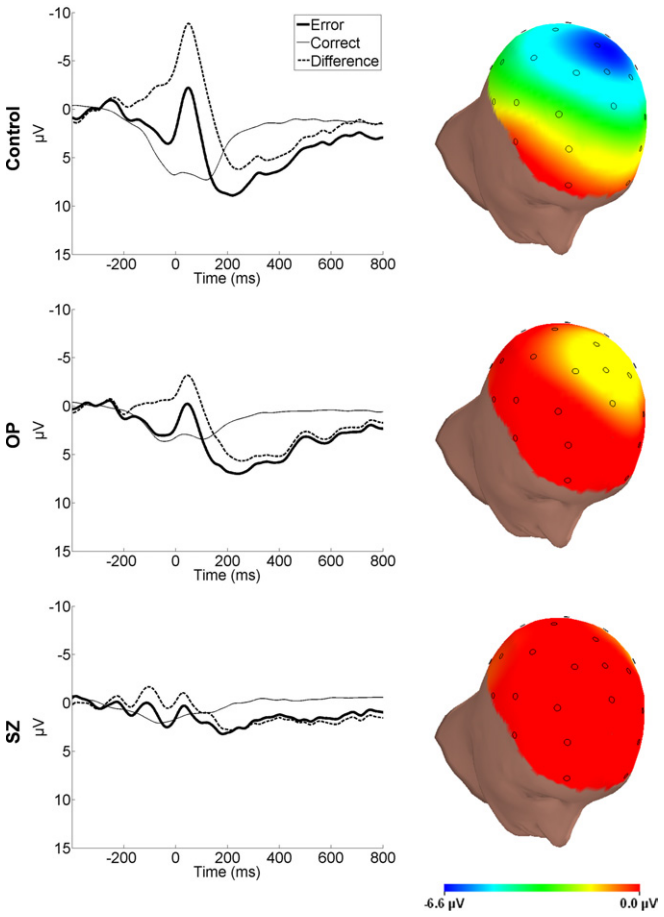

Figure 1. Error-related negativity for control (top), other psychosis (middle), and schizophrenia (bottom) participants. Waveforms show channel Cz, and head maps show the difference between error and correct trials from 0 to 100 msec. OP, other psychosis; SZ, schizophrenia.

ality (42). Of interest was the neuroticism subscale (14,15); the other subscales are presented in Table S1 in Supplement 1.

Archival Measures. Six other patient characteristics were obtained from the 10-year assessment of the cohort: rehospitalizations during the early illness phase (within 4 years of first admission; coded as 0/1 vs. 2+), rehospitalizations during the later phase (between years 5 and 10; 0/1 vs. 2+), employment status (employed vs. not employed), socioeconomic status of the head of household at first hospitalization, premorbid IQ, and social functioning. IQ was estimated using the total number of words read correctly on the Wide Range Achievement Test–Version 3 (43). Social functioning was measured as a sum of three interviewer ratings from the Quality of Life Scale: social activity, social initiative, and sociosexual relations (44,45). Impairment was coded as scores ≤10, which corresponds to moderate difficulties or worse.

Flankers Task. An arrow flankers task was used to elicit an ERN (46). On each trial, five horizontally aligned arrowheads were presented, with half of the trials being compatible ('<<<<<' or '>>>>>') and half being incompatible ('<<><<' or '>><>>'). The arrows were presented in the center of a 19-inch (48.3 cm) monitor and, at a viewing distance of approximately 24 inches (61 cm), occupied 1.3° of the visual field vertically and 9.2° horizontally. The arrows were presented for 200 msec and were followed by an intertrial interval that varied randomly from 2300 msec to 2800 msec. Participants were instructed to press the left or right mouse button, corresponding to the direction of the center arrow, and to respond in such a way as to maximize speed and accuracy. Participants first completed a practice block of 30 trials; the actual task consisted of 11 blocks of 30 trials. At the end of each block, participants received performance feedback: performance <75% correct was followed by "Please try to be more accurate"; >90% by "Please try to respond faster"; and intermediate performance by "You're doing a great job."

Procedure

At the beginning of the session, the study was described and written informed consent was obtained. Eligibility of control subjects was confirmed using the SCID. Patients completed interview measures and the Big Five Inventory. Next, both groups participated in the EEG assessment. They performed multiple tasks during the experiment, and the order of the tasks was counterbalanced across subjects. Patients received $100 for their participation; control subjects received either $80 or $95 depending on the length of the session.

EEG Recording, Processing, and Data Reduction

The EEG was recorded using an elastic cap and the ActiveTwo BioSemi system (BioSemi, Amsterdam, The Netherlands). The signal was digitized at 24-bit resolution with a least significant bit value of 31.25 nV and sampling rate of 1024 Hz, using a low-pass fifth-order sinc filter with −3 dB cutoff point at 208 Hz. Electrodes were measured with respect to a common mode sense active electrode that formed a monopolar channel. Recordings were taken from 34 scalp electrodes based on the 10/20 system (including FCz and Iz) and two electrodes on the left and right mastoids. The electro-oculogram was recorded from four facial electrodes.

Offline analysis was performed using Brain Vision Analyzer software (Brain Products, Munich, Germany). Data were re-referenced to the mastoid average and band-pass filtered from .1 Hz to 30 Hz. The EEG was segmented for each trial, spanning −400 msec to 800 msec relative to the response, and corrected for blinks and eye movements (47). Channels were rejected in each trial using a semi-automated procedure, with artifacts defined as a step of more than 50.0 μV between samples, a difference of 300 μV within a trial, or a maximum difference of less than .50 V within 100-msec intervals. Additional artifacts were identified using visual inspection. Response-locked ERP averages were created for correct and incorrect responses, and the activity from −400 msec to −200 msec served as the baseline. The number of error epochs in the ERP average was similar across groups (SZ: M = 23.48, SD = 16.78; OP: M = 19.53, SD = 14.02; control subjects: M = 25.15, SD = 14.68; $p > .20$). A difference wave approach was used to isolate error-related neural activity by subtracting the ERP waveform on correct trials from incorrect trials (48). The ERN was scored as the mean activity from 0 msec to 100 msec at Cz, and the Pe as the mean activity from 200 msec to 400 msec at Pz. For figures, ERP data were refiltered with cutoffs of .5 Hz to 12 Hz; statistical analyses were conducted with the original filter settings.[1]

Data Analysis

Within-subjects comparisons were conducted first, examining the modulation of the ERN and Pe across correct and error trials. Between-subjects comparisons and associations with ERP components were then analyzed using multiple linear regression. The effect of diagnostic group was examined with two orthogonal sets

[1]A .5 Hz to 12 Hz filter slightly attenuated the ERN (−2.44 vs. −3.01 μV); the patients versus control subjects contrast continued to be significant (adjusted $\beta = .43$, $p < .001$). As expected, the Pe was more strongly attenuated with a .5 Hz to 12 Hz filter (4.24 vs. 6.02 μV); the SZ versus OP contrast was weaker and no longer significant ($\beta = .11$, $p = .24$).

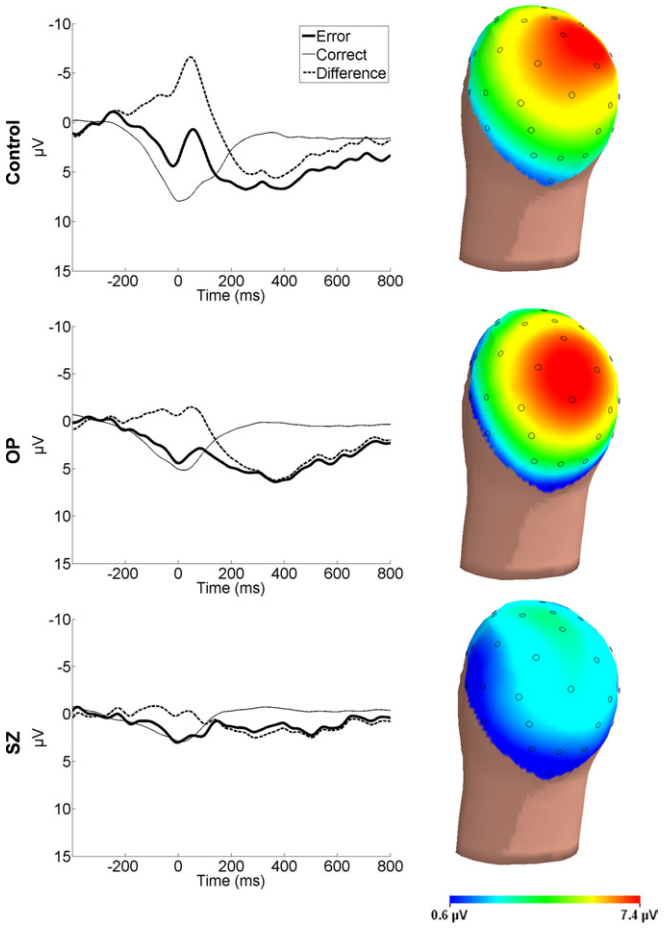

Figure 2. Error-related positivity for control (top), other psychosis (middle), and schizophrenia (bottom) participants. Waveforms show channel Pz, and head maps show the difference between error and correct trials from 200 to 400 msec. OP, other psychosis; SZ, schizophrenia.

of contrast coefficients, one comparing the combined patient group with control subjects and the other comparing the two diagnostic groups with each other, entered simultaneously in a regression model; the combined effect of the two contrasts is equivalent to the main effect of group. In separate steps, demographic variables (age, gender, ethnicity), antipsychotic medication status, and performance (error rate, reaction time) were added as covariates. Likewise, ERN and Pe amplitudes were related to individual difference variables among patients, first using zero-order correlation and then multiple linear regression to adjust for diagnosis, demographic characteristics, antipsychotic medication status, socioeconomic status, and premorbid IQ. To ease interpretation, ERN amplitude was converted to a positive number; positive regression coefficients indicate a direct association. These analyses of individual differences were also repeated stratifying by diagnostic group (Table S2 in Supplement 1). All statistical tests used a two-tailed significance threshold of $p < .05$.

Results

Sample Characteristics

Demographic and clinical variables are presented in Table 1. The groups did not differ on age, gender, or ethnicity. SZ participants were more likely to be taking antipsychotics, although prescribed chlorpromazine equivalent dosages did not differ on average. SZ participants had more severe negative and psychotic symptoms, and at the previous assessment were less likely to be employed or function well socially. Rehospitalization frequency was comparable across groups during the early and later phases of illness. Given the group difference in antipsychotic medication status (using vs. not using), we examined the effect of antipsychotics on ERP variables. Controlling for diagnosis, antipsychotic medication status did not predict ERN amplitude ($p = .84$), but there was a trend for Pe amplitude ($\beta = -.21, p = .09$); we adjusted for antipsychotic status in all subsequent analyses.

Task Performance

Task performance variables are presented in Table 2. After excluding participants with poor performance (<75% correct), the percentage of correct trials was similar across all groups ($p = .18$). Error rates were higher [$F(1,108) = 158.520, p < .001$] and reaction time was slower [$F(1,108) = 461.21, p < .001$] on incompatible trials; neither effect interacted with group (both $ps > .10$). Reaction time was faster on error trials [$F(1,108) = 131.41, p < .001$] and there was posterror slowing [$F(1,108) = 40.19, p < .001$]; neither effect interacted with group (both $ps > .10$). Considering the average of all trials, reaction time varied as a function of group [$F(2,108) = 10.67, p < .001$], such that SZ participants were slower than both OP participants [$t(76) = 2.08, p < .05$] and control subjects [$t(64) = 4.60, p < .001$]; OP participants were also slower than the control subjects [$t(76) = 2.92, p < .01$]. Among patients, overall reaction time was associated with negative ($r = .43, p < .001$) and psychotic symptom severity ($r = .23, p < .05$) but not with disorganized symptoms ($p = .31$). Adding negative and psychotic symptoms as simultaneous predictors of reaction time in a multiple linear regression revealed a unique association with negative symptoms only ($\beta = .40, p < .001$), which remained after controlling for diagnosis, age, gender, ethnicity, antipsychotic medication status, IQ, and socioeconomic status ($\beta = .34, p < .05$).

ERP Measures

Within-Subjects Comparisons. Event-related potential differences across error and correct trials are presented in Table 3. Among the control and OP groups, the ERN and Pe were significantly increased on error compared with correct trials. Among the SZ group, the Pe was significantly increased on error trials, but the ERN was not. For all subsequent analyses, difference scores (i.e., error minus correct) were used for the ERN and Pe.

Group Comparisons. Event-related potential waveforms are presented in Figures 1 and 2, and group comparisons are presented in Table 4. Main effects of group were observed for both the ERN [$R^2 = .27, F(2,108) = 19.83, p < .001$] and Pe [$R^2 = .12, F(2,108) = 7.47, p < .001$].[2] Follow-up contrasts revealed that the ERN was

[2]Group effects were analyzed using two orthogonal contrasts to retain the full sample and maximize statistical power. Comparing just the SZ and control groups yielded effects for both the ERN [$t(64) = 5.30, p < .001$] and Pe [$t(64) = 3.11, p < .01$].

[3]Eight OP participants (17.8%) had substance-induced psychosis. Excluding them, the SZ versus OP contrast for Pe amplitude persisted (adjusted $\beta = .21, p < .05$).

[4]The ERN and Pe were inversely related within the SZ ($r = -.51, p < .01$) and OP groups ($r = -.44, p < .01$); among control subjects, the ERN and Pe were unrelated ($r = -.03, p = .86$).

[5]The patients versus control subjects effect on ERN amplitude was driven by both errors (less negative; adjusted $\beta = -.22, p = .07$) and correct trials (more negative; adjusted $\beta = .20, p < .05$). The SZ versus OP effect on Pe amplitude was driven primarily by a reduction on errors (less positive; $\beta = -.17, p = .09$), not correct trials ($\beta = .02, p = .89$).

Table 4. Hierarchical Linear Regression Comparing ERN and Pe Amplitude Across Groups

Variable	Step	Multiple Regression Coefficient (β)	
		Patients vs. Control Subjects	SZ vs. OP
ERN	1. Initial	.52[a]	.12
	2. Adjust for demographics	.50[a]	.13
	3. Adjust for antipsychotic medication	.48[a]	.11
	4. Adjust for behavioral performance	.40[a]	.08
Pe	1. Initial	.12	.34[a]
	2. Adjust for demographics	.15	.33[a]
	3. Adjust for antipsychotic medication	.05	.21[b]
	4. Adjust for behavioral performance	.08	.21[b]

	Schizophrenia		Other Psychosis		Control Subjects	
Adjusted Scores	Mean	SD	Mean	SD	Mean	SD
ERN	.04	6.03	−1.36	5.23	−6.39	5.34
Pe	4.23	6.72	7.14	5.30	6.27	5.92

Demographic variables are age, gender, and ethnicity. Performance variables are the percentage of errors and the average reaction time across all trials.

ERN, error-related negativity; OP, other psychosis; Pe, error positivity; SD, standard deviation; SZ, schizophrenia.

[a] $p < .001$.

[b] $p < .05$.

blunted among patients compared with control subjects, and this effect persisted after adjusting for all covariates; there was no difference between the SZ and OP groups. A different pattern emerged for the Pe: there was no overall difference between the patients and control subjects, but the Pe was blunted among the SZ group compared with the OP group, and this difference persisted after adjusting for all covariates.[3,4,5]

Individual Differences. Associations within the patient group are presented in Table 5. With regard to clinical variables, ERN amplitude was inversely related to negative symptom severity, even after adjusting for all covariates. There was a trend toward Pe amplitude being inversely related to negative symptom severity, but this effect was further attenuated after adjusting for covariates. Neither the ERN nor the Pe were significantly associated with psychotic or disorganized symptoms (all $ps > .10$). Even after adjusting for covariates, higher neuroticism was associated with an increased ERN among patients. Neither the ERN nor the Pe were related to posterror slowing (both $ps > .30$).

With regard to real world functioning, the ERN was blunted among patients with two or more rehospitalizations during the early phase of the illness, as well as among patients who were unemployed at the previous assessment (Figure 3). Patients who functioned better, as indicated by rehospitalization history and employment status, exhibited a relatively intact ERN, even after adjusting for all covariates. On the other hand, the ERN was not related to social impairment, and no significant effects of functioning were observed for the Pe.

Table 5. Associations with ERP Measures Among Patients

Variable	Association with ERN		Association with Pe	
	Correlation (*r*)	Adjusted (β)	Correlation (*r*)	Adjusted (β)
Symptoms—Total Scores				
Negative	−.22[a]	−.27[a]	−.21[b]	.08
Psychotic	−.13	−.03	−.15	−.07
Disorganized	−.09	−.10	−.10	.00
Real World Functioning				
Rehospitalizations, years 0–4	−.23[a]	−.25[a]	.08	.14
Rehospitalizations, years 5–10	−.03	−.02	−.12	−.02
Unemployed	−.34[c]	−.34[c]	−.20[b]	−.04
Socially impaired	−.07	−.03	−.16	.13
Neuroticism	.27[c]	.26[a]	−.11	−.11
Posterror Slowing	−.10	−.05	−.11	−.08

Adjusted values include diagnosis (schizophrenia vs. other psychosis), age, gender, ethnicity, antipsychotic medication status, premorbid IQ, and socioeconomic status as additional predictors. Error-related negativity amplitude was converted to a positive number, such that positive regression coefficients indicate a direct association and negative coefficients indicate an inverse association. Posterror slowing is the reaction time difference between correct trials following errors and the average of all correct trials.

ERN, error-related negativity; ERP, event-related potential; Pe, error positivity.

[a] $p \leq .05$.

[b] $p < .10$.

[c] $p < .01$.

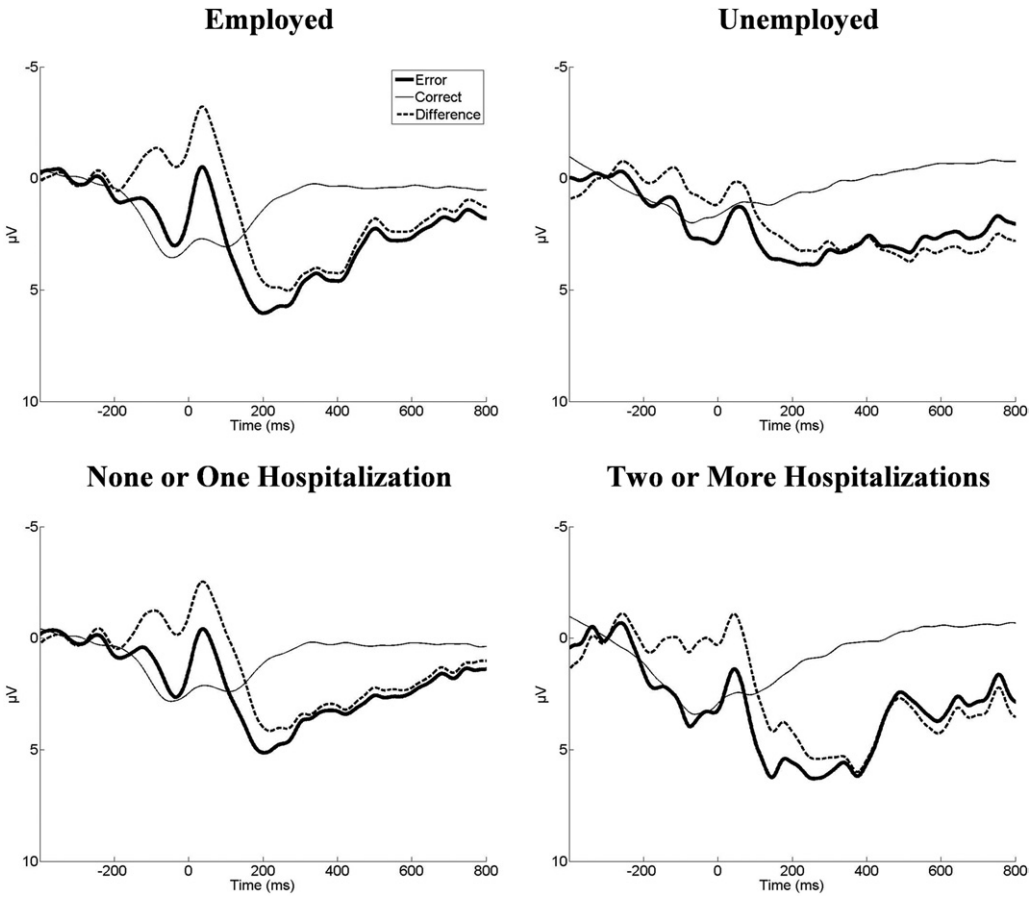

Figure 3. Error-related negativity waveforms among patients, presented for electrode Cz. Patients are grouped by employment status at the previous assessment (top) and rehospitalization frequency during the early phase of the illness (0–4 years; bottom).

Discussion

Consistent with the existing literature, the ERN was blunted among individuals with schizophrenia, indicating deficient error monitoring (4–10). The current study builds upon this finding and sheds new light on abnormal error processing in schizophrenia in three ways. First, a blunted ERN was not specific to schizophrenia. This neural index of error processing was similarly impaired in other psychotic disorders. Second, blunted Pe amplitude showed relatively greater diagnostic specificity and was diminished only among individuals with schizophrenia. This finding is in contrast to prior studies that did not detect group differences in Pe amplitude (7–10) but is broadly consistent with the well-established finding of a reduced P300 in schizophrenia (29,30). Together, these findings suggest that in schizophrenia both the immediate detection and later, conscious awareness of errors are compromised. In other psychotic disorders, the error monitoring deficit appears to be relatively specific to the immediate detection (i.e., ERN), with error awareness being intact (i.e., Pe). Third, across psychotic disorders, impaired error processing related to worse real-world functioning, indicating for the first time that ERP assessment of error processing is associated with clinical characteristics of these illnesses.

In particular, a blunted ERN was associated with unemployment and impairment in community functioning, as indicated by hospitalizations during the first 4 years of illness. Later hospitalization did not predict the ERN, suggesting that the ERN is more closely related to impairment during the acute phase of the illness. Alternatively, the lack of association with later hospitalization may be influenced by the shift toward outpatient care in the late 1990s and early 2000s. Given this promising evidence of clinical utility, it will be important to examine whether ERP measures of error processing are also predictive of future functioning. In one study, ERN amplitude partially normalized following 6 weeks of successful treatment with antipsychotic medication (5), suggesting that abnormal error monitoring is partly influenced by illness state. It will be of interest to re-assess the current sample to test whether the ERN and Pe similarly normalize among individuals who show clinical improvement and whether deficits in error processing predict poorer functioning at follow-up.

Despite being blunted among patients, the ERN was moderated by individual differences in personality in a manner that is consistent with prior work in healthy populations. An increased ERN has been related to negative affect and trait neuroticism (14,15), and the same association was observed here in the patient sample. With regard to symptomatology, blunted ERN amplitude was associated with negative symptom severity. This may reflect diminished motivation to pursue goal-directed activities, which is thought to be the core deficit underlying the negative symptom domain (49). This link is broadly consistent with prior work in healthy populations demonstrating that the ERN is modulated by the motivational significance of errors (50,51), as well as other work suggesting ERN amplitude is enhanced among populations that are especially sensitive to errors (13). Error monitoring is impaired but not broken in psychotic populations, and it is affected by individual differences in personality and symptomatology in expected ways.

It should be noted that the ERP deficits observed here are not a result of poor task performance, with accuracy levels being highly similar across groups and ERN/Pe differences persisting after adjustment for behavioral measures. Thus, there was a dissociation among patients between task effectiveness and neural activity associated with error monitoring. One possibility, as proposed previously (4,7), is that patients were less certain about the appropriate response on individual trials, which would reduce the magnitude of the ERN (52). While Pe magnitude has previously been related to posterror reaction time slowing (26), no association was observed here, and comparable levels of compensatory posterror slowing were observed across patients and control subjects. The patient sample was considerably slower in their overall reaction time, however, suggesting that the task was more difficult for them. Thus, the ERN and Pe may indicate differences in subjective task experience, independent of objective performance.

A strength of the current study is the use of a well-characterized sample, with diagnoses based on a decade of information. Another strength is the use of a relatively large sample, with the schizophrenia group alone being approximately twice as large as in previous reports. Nevertheless, the sample size was limited and allowed us to evaluate only moderate to large effects. In fact, we observed that adjusted ERN amplitude was .25 standard deviations smaller in the schizophrenia group than in the other psychosis group, but this difference was not significant in our study. Therefore, we cannot conclude that ERN amplitude is equivalent across all psychotic disorders, and larger studies may be able to detect more subtle diagnostic specificity in this index.

One limitation of this study is that antipsychotic usage was more common in the schizophrenia group than the other psychosis group. We controlled for medication status in all analyses, which had little influence on the findings. While antipsychotics decrease ERN amplitude among control subjects (53,54), they increase ERN amplitude among individuals with schizophrenia (5). This suggests that the blunted ERN observed here is not simply a byproduct of treatment, but a more definitive analysis would require assessment of neuroleptic-naive patients. Another limitation is that functioning measures were not concurrent with the ERP assessment, which could have made it more difficult to detect significant associations—speaking to the robustness of the observed effects. Lastly, control subjects were not matched to patients on premorbid functioning or socioeconomic status. A primary focus of the current study, however, was to examine functional correlates of abnormal neural activity within the patient sample and for those analyses we controlled for both potential confounds.

The current study advances the literature by clarifying some of the diagnostic and clinical consequences of impaired error processing in schizophrenia. Whereas ERN amplitude is blunted across a broad range of psychotic illnesses, reduced Pe amplitude may be more specific to schizophrenia. In addition, deficits in error processing relate to worse functioning in psychotic illness, including occupational and rehospitalization; this is the first study to relate the ERN to real-world functioning in psychotic populations. Further work is necessary to examine the extent to which the ERN and Pe are sensitive to clinical state and are predictive of future functioning.

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Supplementary material cited in this article is available online.

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