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Relations Among Intelligence, Executive Function, and P300 Event Related Potentials in Schizophrenia

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Abstract: Prior research has demonstrated that the P300 response may be related to neuropsychological functioning in nonclinical samples. However, the nature of this relation is unclear, and its characteristics in schizophrenia are unexplored. We assessed estimated IQ, neuropsychological tests that assess components of executive functioning, and the P300 component of the event-related brain potential elicited by auditory and visual oddball paradigms in individuals with and without schizophrenia. We observed modest relations between P300 indices and neuropsychological tests purported to assess aspects of executive functioning in both diagnostic groups. Furthermore, multiple regression analyses revealed that whereas control participants with higher estimated IQs demonstrated larger P3 amplitudes to attended auditory targets, the opposite relation appeared evident in schizophrenic participants when variance due to Trailmaking A or a continuous performance task was held constant. Additionally, control participants with higher estimated IQs demonstrated shorter P3 latencies to attended visual targets whereas schizophrenic participants did not when variance due to the Tower of London was held constant. These results suggest diagnostic group differences in the association between P300 and IQ and indicate that investigations designed to explore P300-IQ relations should include measures of executive functioning in their models.

Key Words: Schizophrenia, event-related brain potentials, P3, intelligence, executive function.

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Brain activation measured by the P3(00) event-related potential (ERP) is commonly used as a noninvasive measure of information processing. The P3 response that is reliably elicited by a simple auditory oddball task is a well-established index of stimulus classification (e.g., Pritchard, 1986), and anomalous P3 responding is a useful tool to investigate deviant information processing in psychopathology (e.g., Polich and Kok, 1995). For example, individuals with schizophrenia typically demonstrate diminished P3 responses relative to control participants (e.g., Ford et al., 1994; Pritchard, 1986; van der Stelt et al., 2004), a pattern that has been interpreted to reflect impaired attention and working memory.

Investigations of the relation between the latency and amplitude of the P3 response and individual differences in neuropsychological performance have revealed complex and, at times, contradictory results. For example, a number of studies has demonstrated a direct relation between neuropsychological functioning and P3 amplitude and an inverse relation between neuropsychological functioning and P3 latency (e.g., Egan et al., 1992; Jausovec and Jausovec, 2000; O'Donnell et al., 1992; Polich and Martin, 1992; Polich et al., 1990; Walhovd and Fjell, 2003). These findings are generally consistent with the widely accepted psychological mechanisms of the P3 response: P3 amplitude reflects impaired attention allocation and working memory capacity (Fabiani et al., 1998; e.g., Kok, 2001; for a review, see Polich and Kok, 1995); P3 latency reflects speed of stimulus evaluation (e.g., Kutas et al., 1977; Magliero et al., 1984).

Numerous investigations have demonstrated relations between P3 amplitude and latency and neurocognitive performance that do not conform to the general patterns outlined. For example, several studies have demonstrated a direct association between cognitive ability and P3 amplitude, but no relation with P3 latency. Such studies typically have involved more complex tasks that rely to a greater extent on working memory and/or executive function ability, such as higher-order n-back tasks and intelligence tests (Gevins and Smith, 2000; Nittono et al., 1999; Pelosi and Blumhardt, 1992; Pelosi et al., 1992; Polich, 1998). Conversely, other investigations have documented relations between cognitive ability and P300 latency but not amplitude (O'Donnell et al., 1992; Polich et al., 1983; Wright et al., 2002), while others still have demonstrated an inverse relation between P3 amplitude and cognitive ability (e.g., Houlihan et al., 1998; McGarry-Roberts et al., 1992). Such complex and, at times, contradictory findings suggest that the associations between P3 latency and amplitude and cognitive abilities may be dependent on the types of neuropsychological tasks employed.

One of the most robust electrophysiological anomalies associated with schizophrenia is an attenuated P3 amplitude, particularly in the auditory domain (e.g., Egan et al., 1994; Ford et al., 1994; Pfefferbaum et al., 1989). Attenuated P3 responses in schizophrenia have been interpreted to reflect poor context updating and limits on the level of resources available or allocated to a given task, and have been linked to

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a number of neuroanatomical deficits (for a review, see Ford, 1999). It is perhaps not surprising, then, that the cognitive functioning of individuals with schizophrenia is about 1.5 to 2.0 *SD*s below the mean of comparison participants (Hoff et al., 1999). Additionally, individuals with schizophrenia demonstrate particularly striking neuropsychological deficits in tasks that assess frontal lobe and/or executive functioning, and such deficits show relations to neuroimaging measures of frontostriatal functioning and ventricular enlargement (for a review, see, e.g., Callicott et al., 1998; de la Torre et al., 2004).

Despite this evidence that P3 amplitude and latency have been linked to measures of cognitive ability and that individuals with schizophrenia demonstrate attenuated P3 responding and poorer cognitive functioning, relations between the P3 response and cognitive functioning in schizophrenia remain poorly understood. In the current investigation, we assessed P3 responses in auditory and visual oddball paradigms in individuals with and without schizophrenia. We examined relations to neurocognitive performance in tasks that assess executive functioning to evaluate (1) whether P3 amplitudes and latencies are related to intelligence in a nonclinical sample, (2) whether individuals with schizophrenia demonstrate similar patterns of P3-intelligence relations, and (3) the effects on observed P3-intelligence relations when performance on tests of frontal lobe functioning is controlled. Because the P300 response and intelligence are influenced by a number of cognitive factors related to frontal lobe functioning (e.g., attention, working memory), we hypothesized that controlling for these factors would increase our statistical power to detect P3-intelligence relations in these two diagnostic groups.

METHODS

Participants and Materials

All participants provided written informed consent. Twenty-five adults participated, including 13 individuals with schizophrenia (nine males and four females; age mean [*SD*] = 28.2 [10.7]) and 12 controls (nine males and three females; age mean [*SD*] = 29.7 [12.8]). Patients were recruited from psychiatric facilities affiliated with the University of North Carolina. Psychiatric diagnoses were established on the basis of interviews using the Structured Clinical Interview for DSM-IV (First et al., 1996). Patients were in a stable phase of their illness, and most were outpatients who were functioning fairly well and who generally volunteered to participate in more than one research study, including a functional MRI study using a similar oddball task as the one used here (Mitchell et al., 2002). The data presented in the current investigation are from a subsample of participants drawn from a larger cohort described elsewhere (van der Stelt et al., 2004).

Participants completed the Information, Picture Completion, and Digit Span subtests of the Wechsler Adult Intelligent Scale-Revised (WAIS-R; Wechsler, 1981). An estimated full scale IQ was derived from the sum of the age-scaled scores (Kaufman, 1990). This short form of the WAIS-R has been shown to correlate 0.87 with full scale IQ (Allen et al., 1997) and to have a reliability of 0.91 (Gregory, 1999).

Participants completed the following tests of executive functioning via computer: (1) Trailmaking parts A and B, a test that requires participants to draw lines connecting consecutive numbers in part A, and alternating numbers and letters in part B (Reitan and Wolfson, 1985); (2) Tower of London, Version A, a test that requires participants to determine the number of steps required to reorganize one arrangement of objects so that it resembles a particular arrangement (Shallice, 1982); (3) a Continuous Performance Task (CPT) that requires participants to identify consecutively identical numbers from 2-digit, 3-digit, and 4-digit numbers; (4) the 64-item version of the Wisconsin Card Sorting Test (WCST), a test that requires sorting cards with colored shapes based on changing rules (Axelrod et al., 1992; Heaton, 1981); and (5) a visuospatial working memory task, a test that requires recall the location of a dot on the screen after a 5-second delay.

Procedure

Participants completed first a visual oddball task and then an auditory oddball task in a first session, and the neurocognitive battery in a second session. In the visual task, excluding practice blocks, each participant received 10 experimental blocks of stimuli. In the first seven blocks, participants attended to a series of visual stimuli while ignoring intermixed auditory stimuli. Each block consisted of 204 visual stimuli presented consecutively on a computer screen for a duration of 506.4 ms with an interstimulus interval (onset-to-onset) of 1500 ms. Visual stimuli consisted of standard (squares; $N = 1348$, $p = 94.4\%$), target (circles; $N = 41$, $p = 2.9\%$), and novel (different familiar objects; $N = 39$, $p = 2.7\%$) objects. Each block also included 204 binaurally presented, 68 dB sound pressure level (C scale) auditory stimuli presented over earphones. The auditory stimuli were presented consecutively with a variable interstimulus interval of 1300 to 1700 ms (mean = 1500 ms). Auditory stimuli consisted of standard (a pure 1000 Hz tone; $N = 1387$, $p = 97.1\%$) and deviant (a pure 1064 Hz tone; $N = 41$, $p = 2.9\%$) tones, each with a duration of 100 ms (including a 10-ms rise and fall time). Participants were instructed to attend to the visual stimuli while ignoring the auditory stimuli and to make a button-press response each time a visual target stimulus was presented. Frequent standard and infrequent novel stimuli were task-irrelevant and did not require a response. These blocks resulted in four dependent measures of interest: attended visual target amplitude and latency and attended visual novel amplitude and latency.

During the last three blocks, participants attended to auditory stimuli while passively viewing visual stimuli. The auditory stimuli were identical to the ones used in the prior blocks, but the visual stimuli consisted of only one type of visual stimuli (squares). Each of the three blocks consisted of 164 auditory stimuli presented at a constant ISI of 1500 ms and 164 intermixed visual stimuli presented at a variable ISI of 1300 to 1700 ms (mean of 1500 ms). A total of 492 auditory stimuli were presented, consisting of standard (1000 Hz tone; $N = 450$, $p = 91.5\%$) and deviant (1064 Hz tone; $N = 42$, $p = 8.5\%$) stimuli. The participant attended to the auditory stimuli while ignoring the visual stimuli and made a button-press response with the right index finger to each

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auditory target. Participants were instructed to emphasize both speed and accuracy during both tasks. These blocks resulted in two dependent measures of interest: attended auditory target amplitude and latency.

EEG was recorded using tin electrodes mounted in an electro-cap from 30 scalp locations, consisting of Fp1, Fp2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, O1, Oz, and O2, according to the American Electroencephalographic Society (1994) guidelines for standard electrode position nomenclature. The right mastoid served as reference. Bipolar recordings of horizontal and vertical electro-oculogram were made using electrodes at the outer canthi of both eyes, and above and below the right eye, respectively. EEG and electro-oculogram were amplified with a bandpass of 0.15 to 70 Hz, digitized at 500 Hz, and stored on computer disk for offline processing.

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Data Analysis

An estimated IQ score was calculated by summing the age-scaled scores of the three WAIS subtests and then deriving an IQ estimate as outlined in Kaufman (1990). CPT scores were averaged across trials to obtain an average CPT Reaction Time and an average D Prime score that reflected the number of hits in relation to the number of false alarms. Standard methods were used to derive scores from other neuropsychological tests.

The first five trials of EEG data within each block, trials immediately after deviant stimuli, trials with amplifier blocking, and trials with excessive movement activity were not analyzed. Ocular artifact was corrected using regression analysis in the frequency domain. For each participant, stimulus-locked ERPs were computed at each scalp location for each of the stimulus conditions separately for the standards and deviants. The averaging period was 1200-ms, including a 200-ms prestimulus baseline for amplitude measurements. The single-subject ERPs were digitally lowpass-filtered offline at 15.5 Hz.

P300 amplitudes were quantified by computing the amplitude of the largest positive peak in a 300-ms to 700-ms poststimulus latency window, using a 200-ms prestimulus period as baseline. Peak latencies were determined by detecting the data point of maximum positive voltage in the 300-ms to 700-ms poststimulus latency range. Both amplitude and latency values were derived automatically using a computer algorithm (van der Stelt et al., 2004, p. 570).

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RESULTS

P3 ERPs

The P3 responses elicited by visual novel and target stimuli and auditory target stimuli are depicted in Figure 1. Only the target and novel stimuli, and not the standard (data not shown), elicited a P3 component that occurred between about 300 and 700 ms poststimulus, and reaching maximum amplitude at the parietal scalp locations.

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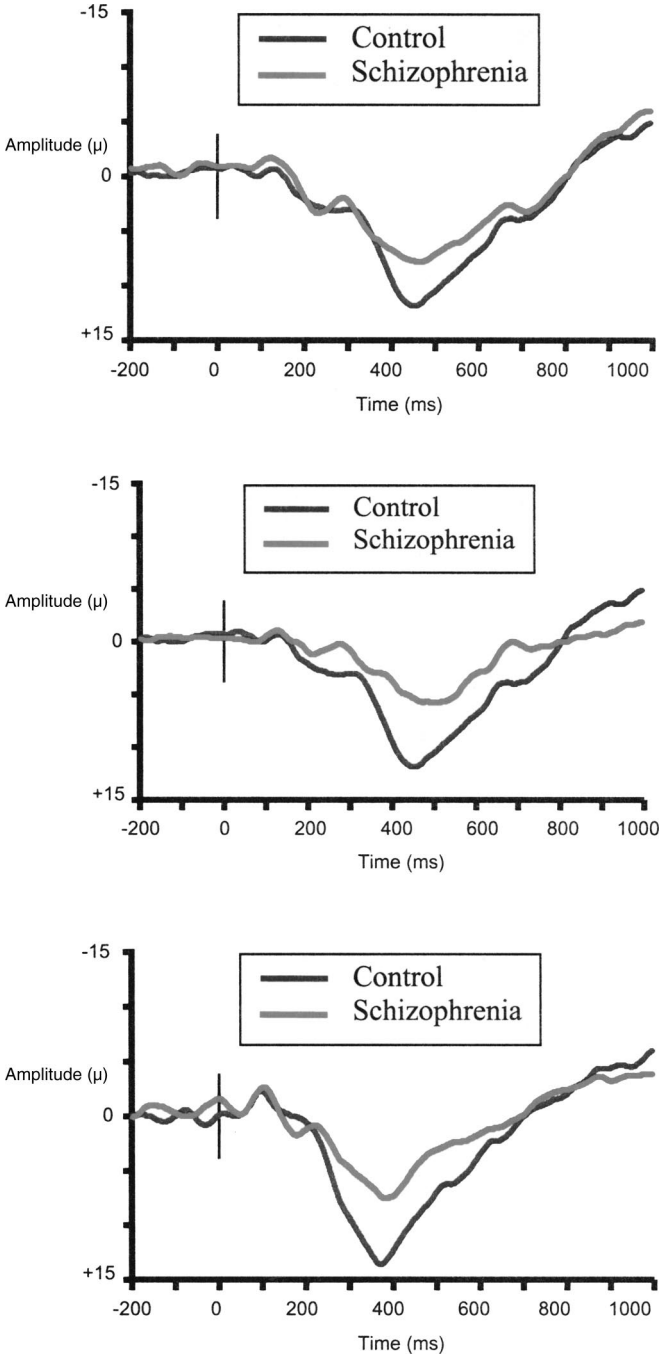

FIGURE 1. Grand average ERP responses recorded at the midline parietal electrode elicited by visual target stimuli (top), visual novel stimuli (middle), and auditory target stimuli (bottom) for control and schizophrenic participants.

Group Comparisons

Table 1 illustrates group means and *SD*s of estimated IQ, P3 amplitudes and latencies, and measures of executive functioning for control and schizophrenic participants. The control group demonstrated higher estimated IQ ($p < 0.001$) and higher scores on the majority of measure of executive functioning relative to schizophrenic participants. Diagnostic groups differed significantly with respect to P3 amplitudes to attended auditory targets, $p < 0.05$, but other measures of P3 amplitude or latency did not reach significance.

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TABLE 1. Group Means and *SD*s of Estimated IQ, P3 ERPs, and Measures of Frontal Lobe Functioning[a]

	Control	Schizophrenic
Estimated IQ***	112.7 (7.4), $N = 11$	95.8 (6.7), $N = 11$
P3 AVN amplitude	9.9 (3.7), $N = 12$	8.4 (2.7), $N = 13$
P3 AVT amplitude	12.8 (5.3), $N = 12$	10.8 (5.3), $N = 13$
P3 AAT amplitude*	14.8 (5.9), $N = 12$	9.6 (3.7), $N = 13$
P3 AVN latency	499.5 (73.9), $N = 12$	498.0 (121.1), $N = 13$
P3 AVT latency	468.6 (75.9), $N = 12$	499.3 (94.1), $N = 13$
P3 AAT latency	365.8 (42.4), $N = 12$	401.5 (57.0), $N = 13$
Tower of London (number correct)	17.2 (3.5), $N = 10$	15.6 (4.1), $N = 13$
CPT average D′*	3.1 (0.5), $N = 11$	2.4 (0.7), $N = 13$
WM mean error (mm)	13.9 (4.7), $N = 11$	19.7 (9.1), $N = 13$
WCST—categories completed*	4.2 (1.4), $N = 11$	2.5 (1.6), $N = 12$
WCST—% perseverative errors	6.1 (4.3), $N = 11$	10.3 (6.4), $N = 12$
Trailmaking A	22.0 (6.6), $N = 11$	27.4 (7.3), $N = 12$
Trailmaking B*	54.2 (32.1), $N = 11$	94.5 (50.4), $N = 12$

AAT, Attended Auditory Target; *AVN*, Attended Visual Novel; *AVT*, Attended Visual Target; *WM*, working memory.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.
[a]All tests are two-tailed.

Zero-Order Correlations

T2 Table 2 indicates the zero-order correlations between estimated IQ, P3 amplitude and latency, and measures of executive functioning for both diagnostic groups. Among the control group (below the diagonal in Table 2), estimated IQ was significantly correlated with a number of measures of executive functioning (Tower of London [$r = 0.765$, $p < 0.05$]; Working Memory [$r = -0.787$, $p < 0.01$]; and WCST categories completed [$r = 0.713$, $p < 0.05$]). Among participants with schizophrenia (above the diagonal in Table 2), however, estimated IQ was significantly correlated with the Tower of London but not with any of the other measures of executive functioning.

One goal of the present investigation was to evaluate previous finding that the P3 response is related to IQ in nonclinical samples. Of note, Table 2 illustrates that all indices of P3 amplitude and latency were not significantly correlated with estimated IQ among either diagnostic group. There were, however, significant correlations between measures of P3 and executive function tests. Among the control group, P3 responses to attended auditory targets were significantly correlated with WCST categories completed (amplitude $r = 0.720$, latency $r = -0.701$, p values <0.05), with Working Memory (latency $r = -0.711$, $p < 0.05$), and with Trailmaking B (latency $r = -0.694$, $p < 0.05$). Among the schizophrenic group, P3 amplitudes were significantly correlated with WCST categories completed (attended visual targets $r = 0.587$, $p < 0.05$), with WCST percent perseverative errors (attended auditory targets. $r = -0.681$, $p < 0.05$), and with Trailmaking A (attended auditory targets, $r = -0.687$, $p < 0.05$).

To investigate further the relations among P3 responses, estimated IQ, and measures of frontal lobe functioning, we conducted hierarchical multiple regression analyses in which measures of executive functioning, diagnostic group membership, and P3 ERPs were specified as predictors of estimated IQ. These analyses were designed to test the unique effects of each of the three predictors on estimated IQ and to test for moderator effects. For example, a significant two-way interaction between group and a P3 index would suggest that the magnitude of the relation between the P3 index and estimated IQ is conditional on the group, and, conversely, that the relation between group and estimated IQ is conditional on the P3 index.

To limit the number of analyses performed, we examined relations involving only those indices of the P3 response that that showed significant zero-order correlations with neuropsychological tests among either diagnostic group. Therefore, measures of electrophysiological activity were constrained to P3 attended auditory amplitudes and latencies to targets and attended visual amplitudes to targets.

A hierarchical structure (Cohen and Cohen, 1983) was used. In the first step, the three predictors were entered simultaneously (i.e., measures of executive functioning, diagnostic group membership, and P3 ERPs). This step was used to test for the main effects of each predictor on estimated IQ removing shared variance with the other predictors. In the second step, the three two-way interaction terms (i.e., measures of executive functioning × diagnostic group membership, P3 ERPs × diagnostic group membership, and measures of executive functioning × P3 ERPs) were entered as a set. In the third step, we entered the executive functioning × diagnostic group membership × P3 ERP three-way interaction term. At each step, we tested the statistical significance of each of the individual regression coefficients in the set just entered and the significance of the incremental variance attributable to the set. We used dummy codes for the categorical variables of diagnostic group membership (1 = control, 2 = schizophrenic). The goal of the present investigation was to assess diagnostic group differences in the relations between neuropsychological and electrophysiological measures. Therefore, to reduce the number of analyses to exam-

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TABLE 2. Zero-Order Correlations Between Estimated IQ, P3 ERPs, and Tests of Executive Functioning in Control Participants (Below Diagonal) and Participants With Schizophrenia (Above Diagonal)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Estimated IQ		−0.497	−0.086	−0.245	0.158	0.119	−0.035	0.694*	0.341	0.069	0.281	0.151	−0.127	0.179
2. P3 AVN amplitude	0.073		0.581*	0.408	−0.194	0.348	0.290	0.228	0.068	0.082	−0.134	−0.104	−0.151	0.033
3. P3 AVT amplitude	−0.058	0.382		0.505	−0.182	−0.073	0.070	0.536	0.455	0.049	0.587*	−0.556	0.518	−0.366
4. P3 AAT amplitude	0.230	0.508	0.745**		−0.314	0.024	−0.364	0.163	0.386	−0.064	0.318	−0.681*	−0.687*	−0.337
5. P3 AVN latency	−0.072	−0.498	−0.231	0.027		0.436	0.592*	−0.286	−0.389	0.189	−0.199	0.378	0.108	0.219
6. P3 AVT latency	0.094	−0.488	−0.062	0.185	0.892***		0.502	0.156	−0.411	0.193	−0.263	0.344	0.086	0.538
7. P3 AAT latency	−0.449	−0.575	−0.387	−0.501	0.143	0.149		0.001	−0.154	0.331	−0.267	0.432	0.219	0.213
8. ToL (# correct)	0.765*	0.079	0.356	0.329	−0.186	−0.093	−0.550		0.564*	0.200	0.482	−0.205	−0.433	0.031
9. CPT average D′	0.357	0.050	0.118	0.377	0.323	0.445	−0.561	0.343		−0.057	0.606*	−0.598*	−0.662*	−0.511
10. WM mean error (mm)	−0.787**	−0.292	−0.349	−0.299	0.360	0.136	0.711*	−0.624	−0.538		−0.641	0.451	0.150	0.495
11. WCST—categories completed	0.713*	0.210	0.504	0.720*	0.101	0.167	−0.701*	0.727*	0.443	−0.441		−0.701	−0.645*	−0.565
12. WCST—% perseverative errors	−0.566	−0.095	−0.296	−0.535	−0.182	−0.165	0.525	−0.714*	−0.264	0.145	−0.909		0.739**	0.874**
13. Trailmaking A	0.012	−0.125	−0.295	−0.286	−0.116	−0.081	0.521	−0.359	−0.802**	0.576	−0.430	0.231		0.542
14. Trailmaking B	−0.366	−0.318	−0.568	−0.572	−0.061	−0.151	0.694*	−0.571	−0.744	0.800	−0.569	0.2733	0.721*	

AAT, Attended Auditory Target; *AVN*, Attended Visual Novel; *AVT*, Attended Visual Target; *ToL*, Tower of London; *WM*, working memory.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

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ined, only two-way interactions involving group will be addressed.

Table 3 illustrates the results of the hierarchical multiple regression analyses. The first-order terms indicated highly significant main effects of group on nearly every measure of executive functioning. Because of how we coded group (i.e., 1 = control, 2 = schizophrenic), these negative *t* values reflect the fact that control participants attained significantly higher scores on these measures than schizophrenic participants.

As indicated earlier, one objective of the present investigation was to assess diagnostic group differences in the relations between estimated IQ and electrophysiological measures when variance due to tests of executive functioning is removed. Table 3 illustrates a total of three significant group × P3 interactions in the prediction of estimated IQ. In the models containing Trailmaking A and CPT D′ as predictors, the group × P3 interactions were significant predictors of estimated IQ for P3 amplitudes to attended auditory targets (the middle of Table 2, *p* values <0.05). Additionally, in the model containing the Tower of London, the group × P3 interactions was a significant predictor of estimated IQ (*p* values <0.05) for P3 latencies in response to attended auditory targets (the bottom of Table 2). Follow-up analyses reveal that these relations were no longer significant when the variance due to Trailmaking A, CPT D′, and Tower of London scores, respectively, were not held constant (*p* values >0.05). In other words, these significant group differences in the relation between estimated IQ and P3 were only evident when variances due to these measures of executive functioning were removed.

Figure 2 illustrates scatterplots of the significant group × P3 interactions separately for control and schizophrenic participants. Figure 2 illustrates that, whereas control participants with higher estimated IQs demonstrated larger P3 amplitudes to attended auditory targets, the opposite relation appears evident in schizophrenic participants in the models where variance due to CPT D′ and Trailmaking A was held constant (the left of Figure 2). In the model where variance due to the Tower of London was held constant (the right side of Figure 2), whereas control participants with higher estimated IQs appeared to demonstrate shorter P3 latencies to attended visual targets, this relation was attenuated in schizophrenic participants.

DISCUSSION

The current study examined relations between P3 responses in auditory and visual oddball paradigms to estimated IQ and executive functioning in individuals with and without schizophrenia. Our central goal was to evaluate the effects of controlling for performance on tests of frontal lobe functioning on P3-intelligence relations. Because the P300 response and intelligence are influenced by a number of cognitive factors related to executive functioning (e.g., attention, working memory), we hypothesized that controlling for these factors would help clarify P3-intelligence relations in these two diagnostic groups. We found that, in the models that controlled for Trailmaking A and CPT D′, the group × P3 interactions were significant predictors of estimated IQ for P3 amplitudes to attended auditory targets. Additionally, in the

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TABLE 3. Results of Hierarchical Multiple Regressions Predicting Estimated IQ From Measures of Executive Functioning, Diagnostic Group Membership, and P3 ERPs[a]

Predictors	Tower of London	CPT Average D′	Working Memory	WCST Categories Completed	WCST % Perseverative Errors	Trails A	Trails B
First-order group							
β	−0.687	−0.610**	−0.750	−0.637	−0.777	−0.771	−0.767
t	−7.078***	−3.269	−4.993***	−4.589***	−5.069***	−4.714***	−4.534***
Sr^2	0.658	0.658	0.658	0.658	0.658	0.61	0.610
P3							
β	−0.155	−0.023	−0.012	−0.182	−0.004	−0.072	−0.072
t	−1.523	−0.164	−0.079	−1.227	−0.025	−0.433	−0.431
Sr^2	0.001	0.001	0.001	0.001	0.001	0.002	0.002
Frontal lobe measure							
β	0.507	0.295	−0.162	0.433	−0.088	−0.069	−0.069
t	4.858***	1.526	−1.033	2.596*	−0.509	−0.389	−0.371
Sr^2	0.198	0.041	0.02	0.097	0.005	0.003	0.003
$R^2_{Increment}$ (set)	0.843	0.7004	0.680	0.748	0.665	0.612	0.612
Two-way interactions group × P3							
β	−0.481	−1.579	0.108	−0.028	0.200	−1.488	0.805
t	−1.267	−1.773	0.19	−0.04	0.341	−1.312	1.063
Sr^2	0.011	0.013	0.009	0.011	0.010	0.001	0.001
Group × frontal lobe measure							
β	−0.118	−0.515	1.639	−0.489	0.907	1.294	1.361
t	−0.238	−0.719	1.965	−0.93	1.195	1.309	1.415
Sr^2	0.001	0.001	0.076	0.013	0.041	0.003	0.052
P3 × Frontal lobe measure							
β	−0.714	−2.332	−0.205	0.156	−0.467	2.08	−0.368
t	−0.965	−1.532	−0.422	0.176	−1.102	3.253**	−0.811
Sr^2	0.008	0.041	0.003	0.001	0.023	0.158	0.014
$R^2_{Increment}$ (set)	0.041	0.055	0.099	0.053	0.078	−0.133	0.041
Three-way interactions							
β	−0.687	−1.506	−0.391	0.035	−0.582	2.74	−0.594
t	−1.06	−1.117	−0.624	0.056	−1.203	2.488*	−1.096
$R^2_{Increment}$ (set)	0.004	0.001	0.004	0.001	0.011	<0.001	0.009
Sr^2	0.01	0.023	0.006	0.001	0.027	0.111	0.025
P3 metric: Latency of responses to attended auditory targets.							
First-order group							
β	−0.704	−0.617	−0.737	−0.686	−0.779	−0.755	−0.754
t	−6.374***	−3.294**	−4.498***	−4.746***	−4.841***	−4.375***	−4.251***
Sr^2	0.658	0.658	0.658	0.658	0.658	0.61	0.61
P3							
β	−0.084	−0.052	0.027	−0.154	−0.008	0.031	0.034
t	−0.751	−0.319	0.173	−0.964	−0.041	0.169	0.185
Sr^2	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Frontal lobe measure							
β	0.466	0.311	−0.155	0.397	−0.09	−0.026	−0.022
t	4.457***	1.546	−1.035	2.444*	−0.491	−0.142	−0.122
Sr^2	0.183	0.042	0.02	0.088	0.005	0.000	0.000
$R^2_{Increment}$ (set)	0.857	0.7017	0.679	0.756	0.664	0.615	0.615
Two-way interactions group × P3							
β	−0.563	−1.530	−0.184	−0.165	0.09	−1.261	−0.932
t	−1.844	−2.599*	−0.404	−0.19	0.141	−2.304*	−1.305
Sr^2	0.021	0.027	0.016	0.014	0.032	0.025	0.610

(*Continued*)

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TABLE 3. (*Continued*)

Predictors	Tower of London	CPT Average D′	Working Memory	WCST Categories Completed	WCST % Perseverative Errors	Trails A	Trails B
Group × frontal lobe measure							
β	−0.402	−0.603	1.693	−0.808	0.836	0.175	0.199
t	−0.822	−0.904	2.18*	−1.298	1.006	0.157	0.320
Sr^2	0.001	0.005	0.078	0.038	0.026	0.022	0.001
P3 × frontal lobe measure							
β	−1.305	−3.071	−0.244	−0.249	−0.369	1.252	−0.635
t	−1.543	−2.178*	−0.565	−0.215	−1.035	2.255*	−0.647
Sr^2	0.02	0.068	0.005	0.001	0.02	0.086	0.000
$R^2_{Increment}$ (set)	0.013	0.092	0.088	0.025	0.074	0.161	0.066
Three-way interactions							
β	−1.034	−2.313	−0.339	−0.238	−0.591	1.345	−0.409
t	−1.753	−1.946	−0.749	−0.375	−1.308	1.894	−0.668
Sr^2	0.024	0.057	0.009	0.002	0.03	0.066	0.01
$R^2_{Increment}$ (set)	0.009	<0.001	0.003	<0.001	0.004	<0.001	0.011
P3 metric: Amplitude of responses to attended auditory targets.							
First-order group							
β	−0.668	−0.652	−0.714	−0.651	−0.763	−0.741	−0.747
t	−6.454***	−3.443**	−4.981***	−4.602***	−5.270***	−4.611***	−4.505
Sr^2	0.658	0.658	0.658	0.658	0.658	0.610	0.61
P3							
β	−0.031	−0.14	−0.194	−0.114	−0.224	−0.163	−0.167
t	−0.278	−0.845	−1.425	−0.811	−1.46	−1.023	−1.038
Sr^2	0.043	0.043	0.043	0.043	0.043	0.022	0.022
Frontal lobe measure							
β	0.433	0.176	−0.121	0.264	0.021	0.019	0.031
t	3.800***	0.786	−0.844	1.687	0.128	0.115	0.175
Sr^2	0.137	0.010	0.012	0.043	<0.001	<0.001	0.001
$R^2_{Increment}$ (set)	0.839	0.712	0.714	0.744	0.702	0.633	0.633
Two-way interactions group × P3							
β	2.329	4.036*	0.757	2.481	2.320	2.200	2.346
t	2.151*	2.502	0.408	1.467	1.538	1.458	1.173
Sr^2	0.034	0.05	0.041	0.033	0.052	0.023	0.024
Group × frontal lobe measure							
β	0.17	0.535	1.19	−0.017	0.732	−0.572	0.145
t	0.324	0.865	1.148	−0.032	1.045	−0.593	0.138
Sr^2	0.002	0.021	0.019	0.001	0.012	0.018	0.004
P3 × frontal lobe measure							
β	0.975	1.468	0.769	1.233	−2.732	−2.253	−2.805
t	0.815	1.133	0.451	1.122	−1.203	−1.549	−1.296
Sr^2	0.006	0.018	0.003	0.018	0.022	0.045	0.034
$R^2_{Increment}$ (set)	−0.043	−0.087	−0.063	−0.052	−0.086	0.087	−0.062
Three-way interactions							
β	1.919	1.548	2.228	0.943	−2.708	−2.905	−2.200
t	1.005	1.039	0.799	1.039	−1.102	−1.193	−0.793
Sr^2	0.008	0.016	0.01	0.016	0.019	0.028	0.014
$R^2_{Increment}$ (set)	−0.003	<0.001	0.007	0.002	0.003	0.017	0.021
P3 metric: Amplitude of responses to attended auditory targets.							

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

[a]First-order terms were entered in an initial step, followed by two-way interaction terms and then three-way interactions. All β values are standardized.

Sr^2, Squared semi-partial correlation; $R^2_{Increment}$ (set), the increment in proportion of variance accounted for by the set of predictors entered in a given set.

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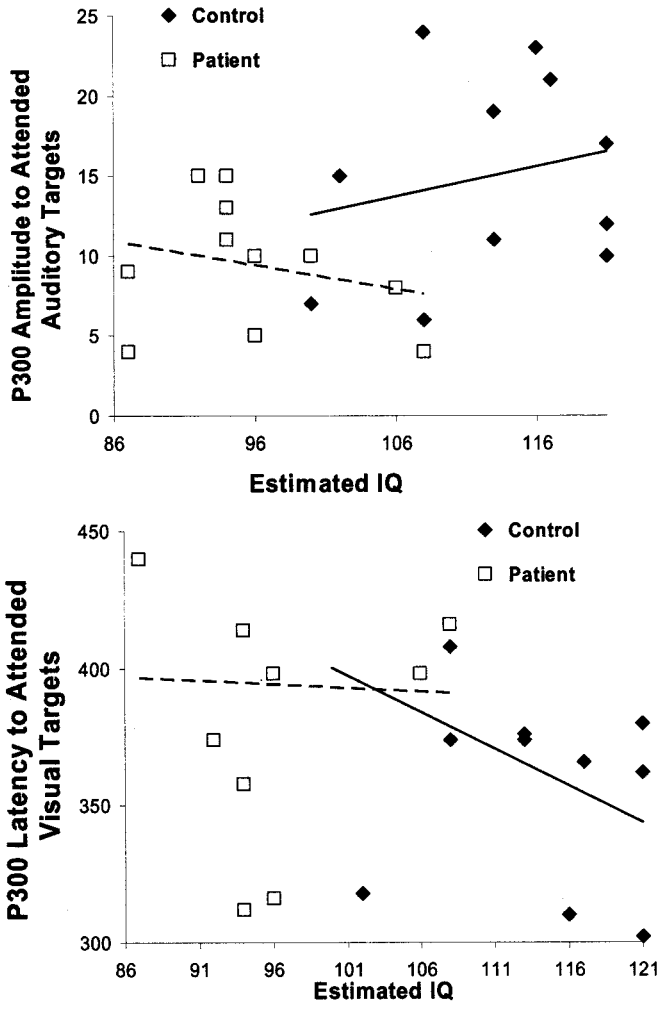

FIGURE 2. Scatterplots illustrating significant group × P3 interactions from hierarchical multiple regression analyses predicting estimated IQ. The top scatterplot includes P3 amplitudes to attended auditory targets and illustrates the significant interactions when either CPT D′ or Trailmaking A was held constant. The bottom scatterplot includes P3 latency to attended visual targets and illustrates the significant interactions when the Tower of London was held constant.

model that controlled for the Tower of London, the group × P3 interaction was a significant predictor of estimated IQ for P3 latencies in response to attended auditory targets. Critically, follow-up analyses reveal that these relations were no longer significant when the variance due to Trailmaking A, CPT D′, and Tower of London scores, respectively, was not held constant. Overall, these findings suggest that an improved understanding of the P3-intelligence relation requires controlling for executive function abilities.

In contrast to the results of hierarchical multiple regression analyses reported, we did not observe any significant bivariate correlations between measures of P3 and estimated IQ in either diagnostic group. Although our failure to find such relations is not surprising given the often contradictory findings in the literature reviewed earlier, such nonsignificant effects in the current investigation are difficult to interpret due to our low power to detect effects given the small sample size.

The Tower of London assesses planning ability, the CPT assesses sustained attention, and Trailmaking A assesses concentration and attention (Lezak, 1995). These executive function skills correlate with intelligence tests in nonclinical (e.g., Ackerman et al., 2005) and schizophrenic (e.g., Chen et al., 1997) samples, and are related to frontal lobe functioning (Heyder et al., 2004). Our findings that diagnostic groups differed significantly in relations between estimated IQ and P3 responses only when variance due to these measures was held constant suggests that IQ-P3 relations may be mediated by these executive function abilities. Because individuals with schizophrenia show increased heterogeneity in executive function capacity relative to controls (e.g., Goldstein and Shemansky, 1995; for a review, see Keri and Janka, 2004), it is likely that schizophrenic individuals with better executive function skills would demonstrate different IQ-P3 relations than schizophrenic individuals with poorer executive function skills. Therefore, the contradictory IQ-P3 relations in the literature may be due, at least in part, to models that did not control for abilities that are mediated by the frontal lobes, and elucidation of the IQ-P3 relation in both nonclinical and clinical samples may require models that include executive functioning.

Results of the current study should be interpreted with caution because of the relatively small sample size and the large number of analyses conducted without correcting for inflated family-wise Type I error rates. However, this liberal data-analytic approach was employed because of the exploratory nature of the current investigation. Nevertheless, the current finding warrants replication with a larger sample. Despite these limitations, the current investigation demonstrated that control participants with higher estimated IQs demonstrated larger P3 amplitudes to attended auditory targets, whereas the opposite relation was evident in schizophrenic participants when variance due to CPT D′ and Trailmaking A was statistically controlled. Additionally, control participants, but not schizophrenic participants, with higher estimated IQs demonstrated shorter P3 latencies to attended visual targets when variance due to the Tower of London was statistically controlled. These findings represent a partial validation that, in nonclinical populations, intelligence correlates with greater P3 amplitudes and smaller P3 latencies, and suggests that such relations are attenuated in schizophrenia. The current study also suggests that future investigations should model executive functioning skills when examining electrophysiological correlates of intelligence.

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