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The relationship between cognitive performance and electrophysiological indices of performance monitoring

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Abstract Studies of electrophysiological indices of performance monitoring, such as the error-related negativity (ERN), posterror positivity (Pe), and N2 components of the event-related potential (ERP), suggest that increased ERN and Pe amplitudes and decreased N2 amplitudes are associated with better cognitive flexibility and cognitive control abilities; however, few studies have directly examined the relationship between cognitive performance and ERP indices of performance monitoring. We examined the neuropsychological profile of 89 healthy individuals who performed a modified flanker task. The neuropsychological domains tested included memory, verbal fluency, and attention/executive functioning. Pearson's correlations and multiple regression analyses showed a significant relationship between measures of attention/executive functioning and ERN amplitude, even when negative affect, reaction time interference, and posterror slowing were controlled. N2 amplitude related only to posterror slowing. The amplitude of the Pe was not significantly related to any cognitive domains. These findings are consistent with recent work indicating that performance monitoring requires attention skills and cognitive flexibility. Implications for the conflict-monitoring and reinforcement-learning theories are discussed.

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Interest in the neural mechanisms underlying performance-monitoring abilities has increased dramatically in the past two decades. This research has specific implications for everyday behavior, because monitoring ongoing performance and adjusting responses is crucial to completion of daily tasks. The tremendous growth in this area of research is reflected in studies of three putative measures of performance-monitoring abilities: the error-related negativity (ERN; also referred to as the error negativity [Ne]), posterror positivity (Pe), and N2 components of the event-related potential (ERP).

The ERN is a frontocentral negative-going deflection in the response-locked ERP that is larger following errors than following correct trials and that peaks approximately 50 ms after response (Falkenstein, Hohnsbein, Hoormann, & Banke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993). The Pe occurs between 200 and 400 ms following participant response, has a centroparietal scalp distribution, and is more positive following error trials than following correct trials (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). Source localization studies have evidenced the anterior cingulate cortex (ACC) as the neural generator of both the ERN (Brazdil, Roman, Daniel, & Rektor, 2005; van Veen & Carter, 2002) and the Pe (Herrmann, Römmler, Ehlis, Heidrich, & Fallgatter, 2004; Overbeek et al., 2005).

The functional significance of the ERN and Pe components remains a matter of debate. Two prominent theories of ERN generation based on computational models, the conflict-monitoring theory of cognitive control and the reinforcement-learning theory, receive the greatest amount of attention. Briefly, the conflict-monitoring theory posits that conflict, which is detected by the ACC, occurs when two or more response options are simultaneously activated; the ERN reflects the neural activity from the competing fast erroneous response and a subsequent corrective response (Carter & van Veen, 2007; Yeung, Botvinick, & Cohen, 2004). The greatest amount of conflict (i.e., the time when both the correct and incorrect response options have the most temporal overlap) occurs immediately after an erroneous response (van Veen & Carter, 2002), with more negative ERN amplitude associated with increased levels of response conflict (Carter & van Veen, 2007; Yeung et al., 2004).

Additional support for the conflict-monitoring theory comes from studies of the N2 component of the ERP. The N2 is a stimulus-locked negative deflection peaking 200–400 ms after stimulus presentation with a frontocentral scalp distribution (Botvinick, Carter, Braver, Barch, & Cohen, 2001; Yeung et al., 2004; Yeung & Cohen, 2006). Source localization studies indicate the ACC as the neural generator of the N2 (Ladouceur, Dahl, & Carter, 2007; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). The N2 is enhanced on incongruent trials as opposed to congruent trials, suggesting a role in the detection of conflict (e.g., Danielmeier, Wessel, Steinhauser, & Ullsperger, 2009; Forster, Carter, Cohen, & Cho, in press). Proponents of the conflict-monitoring theory suggest that the N2 reflects conflict generated by competing responses from task-relevant and task-irrelevant information, with larger N2 amplitudes indicating that individuals attend more to task-irrelevant (i.e., flanker) information (e.g., Yeung & Cohen, 2006).

A second computational model of performance monitoring is the reinforcement-learning theory (RL-ERN; Holroyd & Coles, 2002). The RL-ERN theory proposes that dopaminergic systems in the basal ganglia determine whether performance outcomes are better or worse than expected. The ERN occurs when a mismatch of predicted and actual response outcomes leads to phasic changes in activity of the mesencephalic dopamine system resulting in subsequent disinhibition of apical dendrites in the ACC (Holroyd & Coles, 2002). Consistent with the RL-ERN theory, larger ERN amplitudes occur following unexpected omissions of both reward (Holroyd, Nieuwenhuis, Yeung, & Cohen, 2003) and correct feedback (Yasuda, Sato, Miyawaki, Kumano, & Kuboki, 2004). The amplitude of the ERN is also directly related to the expectedness of the response outcome, with larger (i.e., more negative) ERN amplitudes occurring following unexpected relative to expected outcomes (Holroyd, Krigolson, Baker, Lee, & Gibson, 2009).

Neither the conflict-monitoring nor the RL-ERN theory directly address the relationship between general cognitive abilities and ERN amplitudes, although both theories seem to imply that more negative ERN amplitudes are associated with improved performance. The conflict-monitoring theory does, however, indicate that increased attention to the task is associated with increased ERN amplitudes. For example, emphasis on cognitive performance through increased accuracy, as opposed to speed of response, is associated with larger ERN amplitude (Gehring et al., 1993). Larger N2 amplitude, in contrast, is thought to reflect increased flanker processing, indicative of reduced attentional focus on target stimulus processing (Yeung & Cohen, 2006).

The Pe component of the ERP is thought to be either a reflection of conscious recognition of errors/performance (Endrass, Reuter, & Kathmann, 2007; Larson, Kaufman, Kellison, Schmalfuss, & Perlstein, 2009; Shalgi, Barkan, & Deouell, 2009) or an affective response to conscious errors (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Overbeek et al., 2005). Support for the error awareness hypothesis comes from studies suggesting that Pe amplitude covaries with participants' ability to detect errors (Kaiser, Barker, Haenschel, Baldeweg, & Gruzelier, 1997; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001) and that Pe amplitude positively correlates with the salience of error-inducing information (Leuthold & Sommer, 1999). Evidence for the affective-processing hypothesis of the Pe comes from studies suggesting that individuals who made many errors had smaller Pe amplitudes than those who made fewer, suggesting that they "cared less" (Falkenstein et al., 2000) and that source localization studies evidence the rostral portions of the ACC, involved in affective processing (Bush, Luu, & Posner, 2000), as the specific neural generator of the Pe (Overbeek et al., 2005).

Several studies have interpreted the aforementioned ERN, N2, and Pe findings, along with findings of smaller ERN and N2 amplitudes in individuals with neurologic or psychiatric disorders relative to healthy controls, to indicate that larger ERN and Pe amplitudes are associated with improved performance-monitoring abilities (e.g., Kim, Kang, Shin, Yoo, Kim & Kwon, 2006; Larson et al., 2009; Larson, Kaufman, Schmalfuss, & Perlstein, 2007; Mathalon, Bennett, Askari, Gray, Rosenbloom & Ford, 2003; Olvet & Hajcak, 2008; Themanson, Pontifex, & Hillman, 2008). Further, a recent study demonstrated that larger ERN amplitudes were associated with better academic performance, indicating better performance monitoring and engagement of cognitive mechanisms in individuals with larger ERN amplitudes (Hirsh & Inzlicht, 2010). Thus it seems that larger ERN, N2, and possibly Pe amplitudes may be associated with better cognitive abilities.

In contrast to this view, recent studies show that aerobically fit children and adults made fewer errors and had smaller ERN amplitudes and increased Pe amplitudes than did less-fit individuals (Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Themanson & Hillman, 2006). These authors suggested that their findings represent improved executive control. Studies of the relationship between ERN amplitude, spirituality, and satisfaction with life suggest that decreased ERN amplitudes are associated with a better cognitive framework in which to handle errors (Inzlicht, McGregor, Hirsh, & Nash, 2009; Larson, Good, & Fair, 2010), and a developmental study using two tasks of differing complexity found that the ERN amplitude elicited by the more complex task increased with age and was positively associated with self-correction, potentially reflecting more effective performance monitoring (Hogan, Vargha-Khadem, Kirkham, & Baldeweg, 2005).

Increased insight into the association between ERN, N2, and Pe amplitudes and cognitive abilities has come from the literature on individuals with attention deficit/hyperactivity disorder (ADHD) and schizophrenia. In ADHD, which is generally associated with impairments in various domains of executive function (see Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005, for a review), findings are mixed. Some studies have reported attenuated ERN amplitudes (e.g., Herrmann, Mader, Schreppel, Jacob, Heine, Boreatti-Hümmer et al., 2010; van Meel, Heslenfeld, Oosterlaan, & Sergeant, 2007), and some have reported no differences in ERN amplitudes in individuals with ADHD when compared with healthy controls (Groom, Cahill, Bates, Jackson, Calton, Liddle et al., 2010; Wiersema, van der Meere, & Roeyers, 2005, 2009). Individuals with schizophrenia also tend to have decreased ERN amplitudes when compared with healthy controls (Mathalon, Jorgensen, Roach, & Ford, 2009; Morris, Yee, & Nuechterlein, 2006) and generally demonstrate neurocognitive deficits, particularly in the domains of executive function and attention (see Heinrichs & Zakzanis, 1998, for a review). Notably, Kim et al. (2006) found that ERN amplitudes were positively associated with the Trail Making Test Part B and the Wisconsin Card Sorting Task, both measures of executive function, in individuals with schizophrenia. Control participants showed no such relationship. The absence of a relationship in controls could, however, be due to the small sample used in this study (only 15 control participants). Overall, it remains unclear how ERN, N2, and Pe amplitudes relate to enhanced or impaired cognitive abilities.

One way to examine the relationship between cognitive abilities and electrophysiological indices of performance monitoring is via neuropsychological testing. Neuropsychological testing generally utilizes paper-and-pencil tests to noninvasively measure specific domains of cognitive functioning. For example, the Trail Making Test is one of the most widely used tests in neuropsychology and is thought to measure processing speed and the executive functions of cognitive flexibility and attentional set shifting (Strauss, Sherman, & Spreen, 2006). The Trail Making Test is highly sensitive to most types of brain dysfunction, ranging from mild head injury to schizophrenia (Alterman, McDermott, Cacciola, & Rutherford, 2003; Bachevalier & Loveland, 2006), and even predicts physical impairment and mortality in elderly individuals (Accortt, Freeman, & Allen, 2008).

Utilizing neuropsychological measures, such as the Trail Making Test, allows for comparisons between specific electrophysiological indices and well-established measures of cognitive functioning. The neuropsychological tests for the present study were chosen as a brief yet comprehensive battery of tests that have good psychometric properties and that are considered standards in the field of clinical neuropsychology (Bagiella, Novack, Ansel, Diaz-Arrastia, Dikmen, Hart et al., in press; Lezak, Howieson, & Loring, 2004; Strauss et al., 2006). In addition to processing speed and executive function skills, assessed by the Trail Making Test, we also assessed the domains of attention (primarily working memory), verbal fluency, and verbal memory. Attention/working memory was chosen because of recent research showing a strong association between attention abilities and electrophysiological indices of performance monitoring (e.g., Ladouceur, Conway, & Dahl, 2010), as well as the aforementioned literature relating attention deficits to decreased ERN and increased N2 amplitudes. Verbal fluency was chosen as a domain because of a body of literature suggesting high levels of ACC and left frontal lobe activity during word retrieval (e.g., Fu, Morgan, Suckling, Williams, Andrew, Vythelingum et al., 2002) and other literature suggesting that verbal fluency is a good measure of overall cognitive activation (Lezak et al., 2004). Lastly, verbal memory was chosen as a measure of general cognitive functioning that is largely unrelated to performance-monitoring abilities to see if these measures are related to overall cognitive skills or specific areas of cognitive performance.

The aim of this study was to examine the relationship between indices of performance-monitoring abilities, such as ERN, N2, and Pe amplitudes, and general cognitive abilities as measured by neuropsychological tests in healthy individuals. Such studies are important in the interpretation of ERP alterations in individuals with neurologic and psychiatric difficulties—along with establishing the relationship between performance-monitoring abilities, general cognitive functioning, and specific domains of cognitive performance. We hypothesized that individuals with increased ERN and decreased N2 amplitude would show improved cognitive performance relative to individuals with decreased ERN and increased N2 amplitudes. Given the neuroanatomical and conceptual overlap between electrophysiological measures of performance monitoring and neuropsychological tests of attention/executive skills (e.g., the Trail Making Test described above), we further hypothesized that the specific domains of attention and executive functions would be associated with ERN and N2 amplitude.

Method

Initial study enrollment consisted of 107 right-handed individuals with normal or corrected-to-normal vision recruited from undergraduate psychology courses. Exclusion criteria included: current diagnosis of a psychiatric disorder, neurologic disease, ADHD, learning disability, head injury, substance abuse/dependence, or psychoactive medication use (including stimulants). We excluded 11 participants with fewer than 14 artifact-free trials to compute reliable error-related ERPs and 7 participants who committed fewer than 14 errors on the flanker task (Larson, Baldwin, Good, & Fair, 2010; Olvet & Hajcak, 2009). Final study enrollment, therefore, included 89 individuals (51 female, 38 male). Current depression and anxiety levels were assessed using the Beck Depression Inventory–Second Edition (BDI-II; Beck, 1996) and the State–Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983), respectively. Demographic and neuropsychological summary information are presented in Table 1.

Neuropsychological tests

Neuropsychological tests were administered to all participants prior to the collection of the EEG data. Order of test administration was counterbalanced across participants, with the exception of the test of verbal memory that was administered at the beginning of each testing session. Tests were chosen because they assess the domains of attention/working memory (Digit Span tests from the Wechsler Adult Intelligence Scale–Third Edition [WAIS-III]; Wechsler, 1997), processing speed/executive functioning (Trail Making Test, Parts A and B; Reitan, 1958), verbal fluency (Controlled Oral Word Association Test [COWAT] and category fluency test; Benton & Hansher, 1976), and verbal memory (Rey Auditory–Verbal Learning Test [AVLT]; Rey, 1964). The neuropsychological measures are outlined in detail below.

Digit span forward and backward In this test, increasingly longer strings of numbers are recalled (2–9 numbers) following verbal presentation by the examiner. In the backward version, participants repeat the numbers in reverse order. Span length is defined as the numbers of digits recalled correctly before two strings of the same length were failed. We used separate span scores for Digit Span forward and Digit Span backward. Reliability estimates of the Digit Span range from .84 to .93 (Wechsler, 1997).

Table 1 Demographic and mean summary data (*n* = 89)

	Mean	*SD*	Range
Age (years)	20.7	2.5	18 to 29
Years of education	14.0	1.5	12 to 18
Congruent trial accuracy	0.95	0.05	0.64 to 1.00
Incongruent trial accuracy	0.88	0.07	0.58 to 0.97
Congruent trial response time (ms)	389	31	326 to 485
Incongruent trial response time (ms)	448	33	382 to 534
Incongruent minus congruent time (ms)	58	14	19 to 90
Postcorrect trial response time (ms)	425	30	366 to 509
Posterror trial response time (ms)	434	39	349 to 546
Posterror minus postcorrect difference	9	22	-42 to 77
BDI-II score	5.8	4.7	0 to 21
STAI–State score	31.5	7.8	20 to 62
STAI–Trait score	34.6	8.0	20 to 55
Digit Span forward score	11.1	2.4	5 to 16
Digit Span backward score	7.5	2.4	3 to 13
Trail Making Test Part A (s)	18.9	6.1	11 to 49
Trail Making Test Part B (s)	46.7	12.0	23 to 74
COWAT (total words)	44.2	9.7	21 to 74
Animal fluency (total words)	23.5	4.8	15 to 36
AVLT learning score	54.4	7.0	37 to 72
AVLT short delay recall (out of 15)	11.7	2.4	5 to 15
AVLT long delay recall (out of 15)	11.4	2.8	3 to 15

BDI-II = Beck Depression Inventory–2nd Edition, STAI = State–Trait Anxiety Inventory, COWAT = Controlled Oral Word Association Test, AVLT = Rey Auditory Verbal Learning Test.

Trail making test, parts A and B Trail Making Test, Parts A and B are well-documented measures of visual scanning, processing speed, and task switching (Strauss et al., 2006). In Part A, participants connect consecutively numbered circles as quickly as possible. In Part B, they connect consecutively numbered and lettered circles that alternate between the two sequences. Total completion time is used as the outcome variable. Psychometric studies indicate reliability coefficients above .80 (Strauss et al., 2006).

Controlled oral word association test and category fluency (animals) In this test, participants are asked to produce as many words as possible that begin with the letters F, A, and S in 1 min. For category fluency, participants are asked to name as many animals as possible in 1 min. The reliability of these verbal fluency measures is consistently between .70 and .83 (Strauss et al., 2006).

Rey auditory verbal learning test (AVLT) The AVLT is a measure of verbal memory that consists of two 15-item word lists. Five initial learning trials are presented, with a total learning score calculated by adding Trials 1–5. A distractor list is then presented, followed by a short-delay free recall trial. After a 20-min delay, participants are asked to recall as many of the words as they can remember. We used three different scores from the AVLT in the present study: the learning score (sum of words recalled from Trials 1–5), the number of words recalled at the short delay, and the number of words recalled at the long delay. The AVLT has modest test–retest reliability (up to .70) and correlates significantly with other measures of learning and memory (>.50; see Lezak et al., 2004).

Computerized task

Following completion of the neuropsychological test battery, participants completed a modified version of the Eriksen Flanker Task (Eriksen & Eriksen, 1974) with congruent (e.g., <<<<<) and incongruent (e.g., <<><<) arrow stimuli. Participants were instructed to respond as quickly and accurately as possible with an index-finger buttonpress if the middle arrow pointed to the left and a middle-finger button press if the middle arrow pointed to the right. Stimuli were presented for 100 ms prior to the onset of the target stimulus, which remained on the screen for 600 ms. To decrease expectancy effects, the intertrial interval (ITI) varied randomly between 800 and 1,200 ms, with a mean ITI of 1,000 ms. Three blocks of 300 trials (900 total trials) were presented, with 405 congruent trials and 495 incongruent trials (45% congruent, 55% incongruent).

Electroencephalogram recording and reduction

Electroencephalogram (EEG) was recorded from 128 scalp sites using a Geodesic Sensor Net and an Electrical Geodesics, Inc. (Eugene, OR) amplifier system (20-K nominal gain, bandpass = 0.10–100 Hz). During recording, EEG was referenced to the vertex electrode and digitized continuously at 250 Hz with a 24-bit analog-to-digital converter. Impedances were maintained below 50 kΩ. Data were average-referenced offline and digitally low-pass filtered at 30 Hz. Eye movement and blink artifacts were corrected using the algorithm described by Gratton, Coles, and Donchin (1983).

For the ERN and the Pe, individual-participant response-locked averages were calculated from 400 ms prior to response to 800 ms following the response. We used the –400- to –200-ms time for baseline correction. For the N2, stimulus-locked averages were calculated from –150 ms to 500 ms, with the –150- to 0-ms window used for baseline correction. Electrode sites were chosen based on the scalp distributions of the present data and previous findings that the ERN and N2 are focal over frontomedial locations and the Pe over centroparietal locations (see Falkenstein et al., 1991; Overbeek et al., 2005). Error-related negativity and N2 amplitudes were averaged across four frontocentral electrode sites (numbers 6 [FCz], 7, 106, and Ref [Cz]; see Larson, Fair, Good, & Baldwin, 2010); Pe amplitudes were extracted as the mean amplitude across seven centroparietal electrode sites (Cz, 31, 54, 55 [PCz], 62 [Pz], 79, and 80). Error-trial and correct-trial amplitudes for the ERN were extracted as the mean amplitude of the individual-participant averages from 25 ms and 75 ms postresponse; those for the Pe were extracted as the mean voltage from 200 to 400 ms postresponse. N2 amplitudes were extracted as the mean amplitude from 300 to 350 ms. Difference scores represent the mean value of the difference wave across the aforementioned time windows.

Statistical analyses

Descriptive statistics were calculated for all study variables. Differences between congruent and incongruent trials, and/or error and correct trials, for RTs, error rates, and ERP indices were examined using within-subjects paired-samples *t* tests. Reduction of measures of cognitive and affective functioning was completed by conducting a factor analysis with principal-axis factoring and a promax rotation. We chose principal-axis factoring with a promax rotation in order to extract items with shared variance and allow for a relationship between factors, as one would expect with cognitive performance variables (Hair, Anderson, Tatham, & Black, 1998). We selected factors based on eigenvalues greater than 1.00, examination of the scree plot deflection, and interpretability. Items with a pattern matrix value greater than or equal to .40 were considered to be significantly loading on a factor. Pearson's correlations were used to examine the relationships between study variables. Separate multiple regression analyses were then used to determine the independent predictors of ERN and Pe amplitude. Predictors for both models included total posterror slowing (i.e., posterror minus postcorrect trial time), flanker interference reaction time (RT; i.e., incongruent minus congruent RT), memory domain score, attention/executive domain score, verbal fluency domain score, and negative affect domain score. We reported the variance inflation factor (VIF) for all regression models in order to ensure that the independent variables were not multicollinear (Kleinbaum, Kupper, Muller, & Nizam, 2007).

Results

Behavioral data

Indices of behavioral performance are presented in Table 1. Correlations between the overall accuracy and overall RT data showed no significant speed/accuracy trade-off, *r*(87) = .02, *p* = .83. Analysis of the accuracy data revealed that participants committed significantly more errors to incongruent than to congruent trials, *t*(88) = 12.99, *p* < .001. For RTs, participants exhibited longer RTs to incongruent than to congruent trials, *t*(88) = 38.23, *p* < .001. Participants also showed significantly slower RTs on trials following errors as compared with trials following correct responses, *t*(88) = 3.84, *p* < .001.

Event-related potential data

Response-locked error-trial waveforms contained an average of 45.38 ± 29.69 trials; correct-trial waveforms contained an average of 683.73 ± 111.63 trials. Stimulus-locked congruent trials contained an average of 356.11 ± 31.87 trials, and incongruent trials contained an average of 402.06 ± 44.04 trials. Since we used a mean amplitude procedure for calculating ERP amplitudes, the large difference between the numbers of error trials and correct trials did not inappropriately bias the data (see Luck, 2005). Grand average ERP waveforms reflecting the ERN, Pe, and N2 waveforms are presented in Fig. 1.

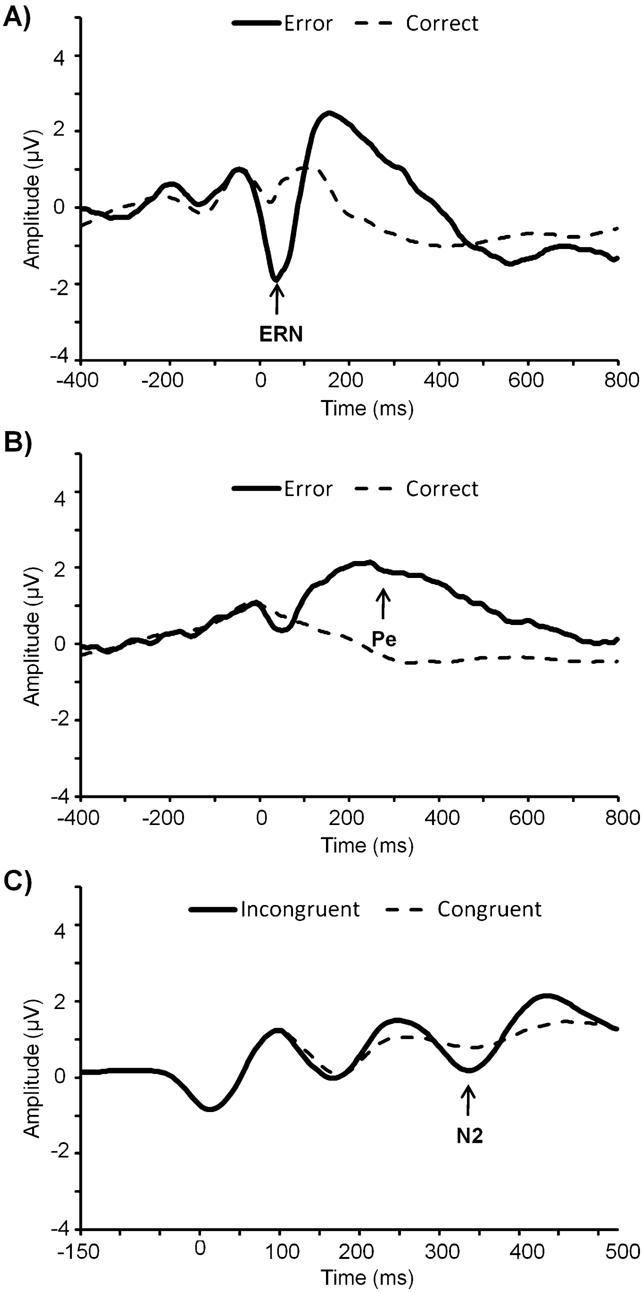

Fig. 1 **a** Grand average ERP waveforms depicting response-locked correct- and error-related activity averaged across frontomedial electrode locations for the ERN. **b** Grand average response-locked ERP waveforms for the Pe averaged across centroparietal electrodes. **c** grand average stimulus-locked ERP waveforms for the N2 averaged across frontocentral electrodes

Consistent with expectations for the ERN, comparison of error-trial and correct-trial ERPs averaged across frontocentral electrode sites revealed a negative deflection that was larger following error trials than following correct trials, *t*(88) = 8.51, *p* < .001. For the Pe, there was a larger centroparietal positivity following error trials than following correct trials, *t*(88) = 7.53, *p* < .001. Similarly, N2 amplitude was more negative for incongruent trials than for congruent trials, *t*(88) = 4.78, *p* < .001.

Factor analysis

To reduce the possibility of Type I error in the comparisons of electrophysiology with cognitive and affective variables, we reduced cognitive and affective study measures into domain composite scores. To accomplish this, all neuropsychological test scores and scores on measures of negative affect were entered simultaneously into a factor analysis using principal-axis factoring with promax rotation. This analysis yielded four separate factors with eigenvalues greater than 1 (eigenvalues = 3.3, 2.1, 1.5, 1.2) that accounted for 68.46% of the variance in the scores (additional eigenvalues = 0.9, 0.5, 0.5, 0.4, 0.4, 0.2, 0.2, 0.2). The four-factor solution was adequately interpretable. As can be seen in the rotated pattern matrix (Table 2), the tests loaded onto factors that we interpret to represent negative affect, attention/executive functioning, verbal fluency, and memory abilities. This interpretation is largely consistent with the domains these measures are designed to assess (Lezak et al., 2004; Strauss et al., 2006).

Based on the factor structure of our measures, we calculated four composite scores by creating *z* scores (*M* = 0, *SD* = 1) for each measure based on the present sample data. We used the inverse of the score for the Trail Making Tests because a higher score on these tests indicates worse performance. Composite function index scores were then created by averaging the *z* scores within each cognitive domain. The negative affect domain was calculated using the average of the *z* scores from the BDI-II, STAI–State, and STAI–Trait. The attention/executive domain was calculated using average of the *z* scores from the Digit Span forward and backward tests and from the Trail Making Test Parts A and B. The verbal fluency domain was calculated using the average of the COWAT and category fluency *z* scores. The memory domain was calculated using the average of the AVLT immediate recall, short-delay, and long-delay *z* scores.

Table 2 Pattern matrix values from the factor analysis

	Factor 1 Memory	Factor 2 Negative Affect	Factor 3 Attention/ Executive	Factor 4 Verbal Fluency
BDI-II	–.01	**.69**	.06	.10
STAI–State	–.04	**.70**	–.06	–.12
STAI–Trait	.04	**.95**	–.01	.03
Digit Span forward	–.09	.17	**.51**	.01
Digit Span backward	.16	.05	**.67**	–.10
Trail Making Test Part A	.02	.06	**–.48**	–.01
Trail Making Test Part B	.06	.14	**–.67**	–.09
COWAT	–.01	–.01	–.08	**.79**
Category fluency	.06	.06	.13	**.51**
AVLT learning	**.81**	.03	.10	–.07
AVLT short delay	**.80**	.07	–.03	.10
AVLT long delay	**.93**	–.10	–.09	.01

Values above .40 are in bold print. BDI-II = Beck Depression Inventory–2nd Edition, STAI = State–Trait Anxiety Inventory, COWAT = Controlled Oral Word Association Test, AVLT = Rey Auditory Verbal Learning Test.

Relationships between electrophysiology and cognitive functioning

Pearson's correlations between ERP amplitudes, behavioral performance, and cognitive domain scores are presented in Table 3. There was a significant inverse relationship between the ERN minus correct-related negativity (CRN) difference and the attention/executive composite score. There was also a significant correlation between ERN amplitude and the attention/executive composite. Amplitude of the incongruent-trial N2 was significantly related only to the degree of posterror slowing.

We next wanted to assess the unique predictive contribution of each of the individual domains to ERN, Pe, and N2 amplitudes. We therefore conducted three separate multiple regression analyses, with the error- minus correct-trial difference scores for the ERN and the Pe and the incongruent minus congruent difference for the N2 as the dependent variables. Difference scores were chosen in order to isolate error- and conflict-related activity, as well as to control for individual differences in ERP amplitudes.[1] Findings from the regression models are summarized in Table 4. The modest correlations between the independent variables may have led to some attenuation in the overall predictive value of the regressions because of item collinearity; however, the VIFs for the independent variables in the regression models were within acceptable limits. For the model with ERN difference score as the dependent variable, the only measure that was a significant predictor was the attention/executive composite, although the overall model was not statistically significant, *F*(6, 82) = 1.51, *p* = .19, and only accounted for 10% of the variance in ERN amplitude. Scatterplots of the relationship between the attention/executive composite and both ERN amplitude and ERN

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[1] Separate regression analyses were also conducted with the dependent variables of ERN amplitude, CRN amplitude, correct-trial Pe amplitude, error-trial Pe amplitude, congruent-trial N2 amplitude, and incongruent-trial N2 amplitude. None of the models were statistically significant. Consistent with the difference score findings, the attention/executive composite score remained significant as a predictor of ERN amplitude, β = – .24, *p* = .04. There were no additional significant predictors of ERN or CRN amplitude. The memory composite score significantly predicted both correct-trial Pe amplitude, β = .23, *p* = .05, and congruent-trial N2 amplitude, β = .25, *p* = .04. Posterror slowing significantly predicted both congruent-trial N2 amplitude, β = .24, *p* = .04, and incongruent-trial N2 amplitude, β = .27, *p* = .02. There were no additional significant predictors in any models.

Table 3 Pearson's correlations for ERP amplitudes and behavioral, affective, and cognitive variables

	ERN	ERN Difference	Error Pe	Pe Difference	N2 Incongruent	N2 Difference
RT interference	–.06	–.03	.01	.04	–.03	–.12
Posterror slowing	–.01	–.08	.12	.07	.21*	.12
Memory	–.01	–.11	–.05	–.14	.11	–.12
Verbal fluency	–.10	–.15	.02	.06	.05	–.03
Attention/executive	–.24*	–.27**	–.12	–.17	–.03	–.08
Negative affect	.07	.09	.04	.07	–.09	–.08

* $p < .05$. ** $p < .01$

difference score amplitude are presented in Fig. 2.[2] The regression model for Pe amplitude was not significant, $F(6, 82) = 1.04$, $p = .41$. The model accounted for 7% of the variance in Pe amplitude, and there were no significant predictors. When N2 difference score was included as the dependent variable, the overall model was not significant, $F(6, 82) = 0.81$, $p = .56$, accounting for 6% of the variance; none of the independent variables were significant predictors.

Discussion

Our results indicate that larger ERN amplitude in healthy individuals is associated with improved performance in specific domains of cognition, but not in all cognitive abilities. Specifically, measures of executive functions and attention/working memory were significantly related to the amplitude of the ERN, whereas measures of memory, verbal fluency, RT interference, posterror slowing, and negative affect were not. The association between ERN amplitude and executive/attention processes held when measures of negative affect and other cognitive functions were controlled using multiple regression. These results support the idea that the ERN represents a cognitive process wherein attention and executive control are required to monitor the presence of errors and subsequently to adjust response behavior to optimize performance levels (Carter & van Veen, 2007; Yeung et al., 2004).

These findings are consistent with previous research indicating that ERN amplitude is modulated by attention to performance and the environment. For example, one of the first studies of the ERN showed increased ERN amplitude when individuals were instructed to attend to the accuracy of their responses, rather than to response speed (Gehring et al., 1993). Similarly, when attention to the task is enhanced by including an observer or monetary reward, ERN amplitude increases (Hajcak, Moser, Yeung, & Simons, 2005). Increased ERN amplitudes are also seen in individuals with personality profiles associated with increased task engagement, such as high agreeableness, behavioral shame, and empathy (Ladouceur et al., 2010; Larson, Fair et al., 2010; Santesso & Segalowitz, 2008; Topps, Boksem, Wester, Lorist, & Meijman, 2006). Taken together, the findings indicate that the ERN may be a relatively robust neurobiological indicator of task engagement and executive control processes.

These findings seem consistent with both the conflict-monitoring model of the ERN and the RL-ERN theory. Yeung et al. (2004) originally concluded that larger ERN amplitudes may be evidenced in individuals focusing attention more strongly on the target stimulus and attempting to ignore flanker information in order to prevent errors on incongruent trials (see also Yeung & Cohen, 2006). More focused attentional control should be followed by strong ACC activation (Botvinick, Cohen, & Carter, 2004), which was originally supported by findings in an fMRI study (Kerns, Cohen, MacDonald, Cho, Stenger & Carter, 2004). However, the present findings offer the first empirical support of a positive correlation between ERN amplitude, putatively evidencing ACC activation, and measures of attention and executive function, giving further strength to this hypothesis. For the RL-ERN theory, dopaminergic activity signals whether events are worse than anticipated (Holroyd & Coles, 2002). This coincides with the role of dopamine in selective attention (Servan-Schreiber, Bruno, Carter, & Cohen, 1998) and in brain-imaging studies of ADHD suggesting that reduced dopamine may underlie inattention symptoms (e.g., Volkow, Wang, Newcorn, Fowler, Telang, Solanto et al., 2007).

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[2] Examination of the scatterplot indicated possible outlying values. Thus, we calculated the centered leverage values, externally Studentized residuals, and influence statistics for the regression with ERN difference score as the dependent variable, as suggested by Cohen, Cohen, West, and Aiken (2003). Using the values suggested by Cohen et al. for each of the diagnostic tests, we identified six cases that were potential outliers. We excluded these cases and reran the regression analyses. The overall model was statistically significant, $F(6, 76) = 2.25$, $p = .05$, accounting for 15% of the variance in ERN difference score amplitude. The attention/executive domain remained the only significant predictor, $\beta = -.25$, $p = .03$. Given the absence of change to the pattern of results when the potential outliers were excluded, we elected to keep all individuals in the models in order to most fully represent our data.

Table 4 Multiple regression models with ERN, Pe, and N2 difference amplitude as the dependent variables

Variables	R^2	*p* Value	*B* (*SE*)	Beta	*p* Value	VIF
DV: ERN difference amplitude	.10	.19				
RT interference			–.01 (.02)	–.03	.81	1.05
Posterror slowing			–.01 (.01)	–.10	.37	1.14
Memory			–.05 (.26)	–.02	.84	1.21
Attention/executive			–.68 (.33)	–.23	.04	1.14
Verbal fluency			–.29 (.28)	–.12	.32	1.24
Negative affect			.18 (.26)	.07	.50	1.06
DV: Pe difference amplitude	.07	.41				
RT interference			.01 (.02)	.03	.76	1.05
Posterror slowing			.01 (.01)	.11	.32	1.14
Memory			–.30 (.34)	–.10	.38	1.21
Attention/executive			–.71 (.42)	–.19	.10	1.14
Verbal fluency			.53 (.36)	.17	.15	1.24
Negative affect			.19 (.33)	.06	.58	1.06
DV: N2 difference amplitude	.06	.56				
RT interference			–.01 (.01)	–.13	.23	1.05
Posterror slowing			.01 (.01)	.13	.26	1.14
Memory			–.13 (.12)	–.13	.28	1.21
Attention/executive			–.08 (.14)	–.06	.62	1.14
Verbal fluency			.05 (.12)	.05	.69	1.24
Negative affect			–.08 (.11)	–.08	.48	1.06

VIF = variance inflation factor.

The results of this study have implications for studies of performance monitoring and the ERN in individuals with psychiatric and neurologic difficulties. For example, several studies have shown a reduced-amplitude ERN in individuals with neurologic difficulties such as traumatic brain injury (Larson et al., 2007; Pontifex, O'Connor, Broglio, & Hillman, 2009), schizophrenia (Mathalon et al., 2009; Morris et al., 2006), and ADHD (e.g., Wiersema et al., 2005). The results of the present study also support and extend previous findings demonstrating a positive association between neuropsychological test scores of set-shifting and ERN amplitude in schizophrenia (Kim et al., 2006). Reduced-amplitude ERNs in these groups were likely contributed to by deficiencies in executive and attentional processes that influence performance monitoring. We should note, however, that directionality cannot be determined from the present data. It is more likely that executive and attentional processes are part of a similar underlying executive/cognitive control system.

The nonsignificant relationship between measures of response-related electrophysiology and posterror slowing seems counterintuitive but is consistent with the recent orienting account for posterror slowing (Notebaert, Houtman, Van Opstal, Gevers, Fias & Verguts, 2009). In this account, posterror slowing is simply a reflection of reorienting to the task after infrequent events or feedback. This was evidenced by results indicating slowing after infrequent correct and incorrect feedback signals (Notebaert et al., 2009). We would expect more attentive individuals to focus more on the task and not to be distracted by infrequent events such as errors. This heightened focus would result in not needing to reorient, and thus decreased posterror slowing relative to individuals lower in attention. However, our present posterror slowing analyses utilized a between-subjects approach. It is possible that examining posterror slowing within subjects (e.g., looking at variations between ERN amplitude and level of posterror slowing within subjects) could yield different results.

The absence of a relationship between Pe amplitudes and attention seems to contradict the error awareness hypothesis, according to which the Pe reflects conscious recognition of erroneous responses. Thus, more attentive individuals should attend more to errors, as reflected in Pe amplitude (Kaiser et al., 1997; Leuthold & Sommer, 1999; Nieuwenhuis et al., 2001). The present results may lend support to an alternative error awareness hypothesis that the Pe simply reflects the process leading to error awareness instead of reflecting error salience or degree of awareness (Overbeek et al., 2005). Importantly, however, our measures of attention/executive skills were not direct measures of attention to the task. Thus, inferences as to the functional significance of the Pe based on these data should be considered speculative at best.

Contrary to our hypothesis, N2 amplitude was not associated with measures of attention/executive function. According to the conflict-monitoring theory, attenuated N2 amplitudes should be associated with increased attention to

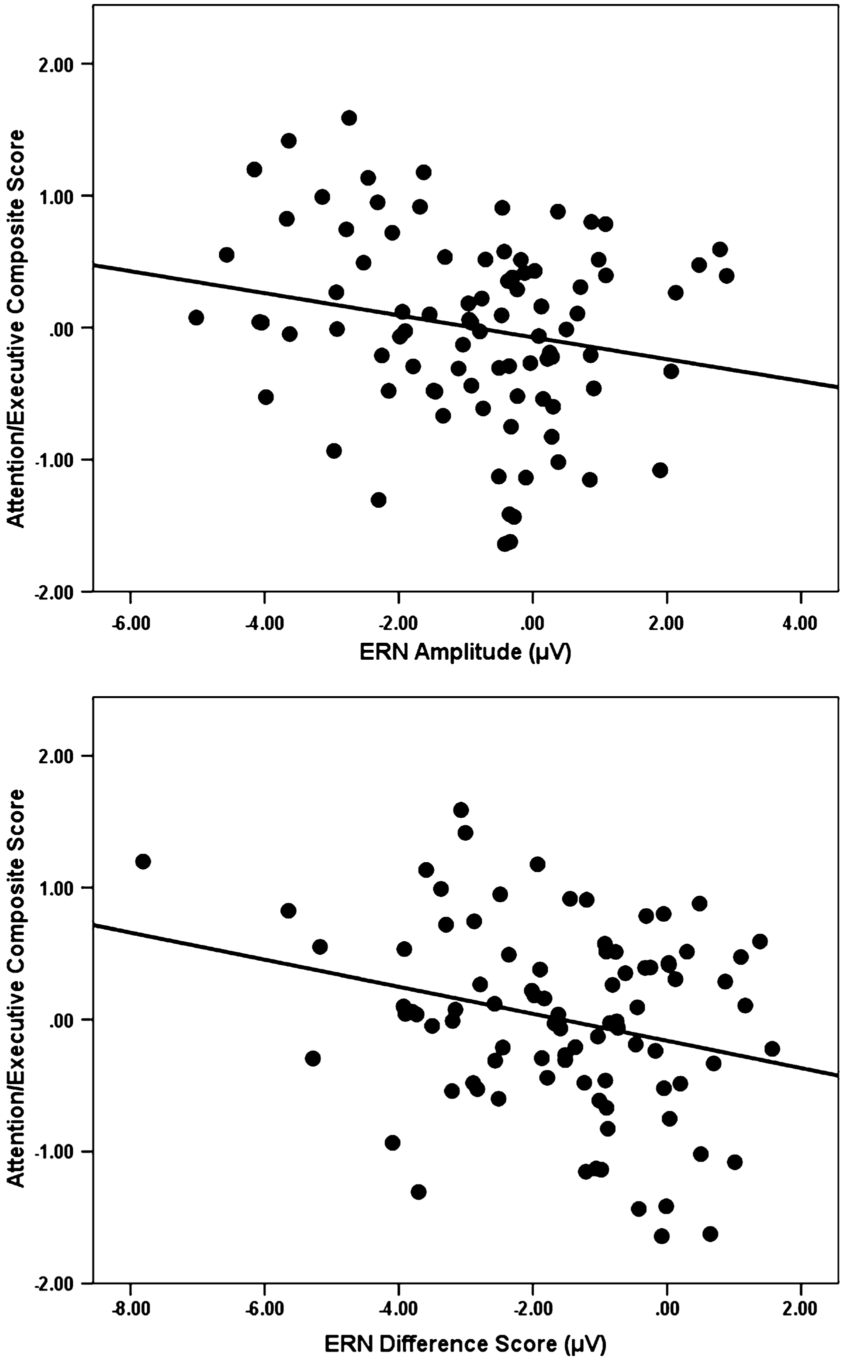

Fig. 2 Scatterplots of the relationship between the attention/executive composite and ERN amplitude (*top*) and between the attention/executive composite and ERN difference score amplitude (*bottom*)

the stimulus and decreased attention to flanker information (Yeung & Cohen, 2006). Specific to this study, decreased N2 amplitude was hypothesized to relate to increased levels of attention, suggesting more effective focus on stimulus processing as opposed to task-irrelevant information. However, our measures of attention were not trial-specific and focused primarily on working memory processes, which may account for this nonsignificant finding. N2 amplitude may be related to selective attention but not to the measures of overall attention/executive function used in this study. Furthermore, findings of a significant positive correlation between incongruent N2 amplitudes and posterror slowing seem consistent with the conflict-monitoring theory. Increased N2 amplitude should be associated with augmented recruitment of attentional control or cognitive resources for subsequent trials (Braver, Barch, Gray, Molfese, & Snyder, 2001; Kerns et al., 2004). The aforementioned correlation may possibly suggest that decreased N2 amplitude may be directly associated with less effective recruitment of cognitive resources after high-conflict trials. This may result in poorer task performance, such as longer posterror slowing.

Some limitations of this study should be considered. First, the executive functioning and attention tasks we used provide only limited data on these domains, and the measure of attention (Digit Span) focused primarily on working memory abilities. The goal of this study was to utilize a comprehensive yet quickly administered battery of tests. Future studies should provide increased depth in the tests of these domains. Some potential measures for inclusion might include the Stroop task, the Wisconsin card sorting task, the Trail Making Test Part B minus Trail Making Test Part A difference, or a continuous performance test. Second, we did not include a measure of intelligence. It is possible that intelligence scores moderate the relationship between cognitive domain scores and electrophysiological measures, although a recent study from our group showed no relationship between intelligence scores and ERN/Pe amplitudes in children (South, Larson, Krauskopf, & Clawson, 2010), and Kim et al. (2006) also showed no relationship between ERN amplitude and intelligence scores. Third, it is possible that there are interactions between negative affect and cognitive domain scores in the prediction of electrophysiological variables. Follow-up studies in individuals with an increased range of negative affect will be necessary to test this possibility. Fourth, our overall regression models were not statistically significant. This is likely due to the fact that some cognitive domains are not related strongly to performance monitoring.

Overall, the findings from the present study indicate that larger (i.e., more negative) ERN amplitude is associated with improved performance in the specific cognitive domains of attention and executive functioning, but not with overall cognitive performance across all domains. These findings are consistent with recent work indicating that ERN amplitude is modulated by the degree of attention to task performance and requires both evaluative and regulative cognitive (i.e., executive) control processes. Further research is needed to elucidate the roles of attention, executive functions, and affective processes on the ERN in individuals with affective disturbances.

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