Psychophysiology, 47 (2010), 192–196. Wiley Periodicals, Inc. Printed in the USA.
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DOI: 10.1111/j.1469-8986.2009.00877.x

BRIEF REPORT

Error-related negativity predicts academic performance

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Abstract

Activity in the anterior cingulate cortex (ACC) has been linked to the processes of error detection and conflict monitoring, along with the subsequent engagement of cognitive-control mechanisms. The error-related negativity (ERN) is an electrophysiological signal associated with this ACC monitoring process, occurring approximately 100 ms after an error is made. The current study examined the possibility that individual differences in ERN magnitude would predict performance outcomes related to cognitive control. Undergraduate students completed a color-naming Stroop task while their neural activity was recorded via electroencephalogram. Results indicated that a larger ERN following errors was significantly correlated with better academic performance as measured by official student transcripts. A greater ability to monitor performance and engage cognitive-control mechanisms when needed thus appears associated with improved real-world performance.

Descriptors: Anterior cingulate cortex, Error-related negativity, Electrophysiology, Cognitive control, Academic performance

The anterior cingulate cortex (ACC) has been implicated in performance monitoring and conflict detection in humans (Carter et al., 1998; MacDonald, Cohen, Stenger, & Carter, 2000; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). During situations of high response conflict, activity in the ACC engages the cognitive-control mechanisms of the prefrontal cortex (PFC), subsequently improving behavioral regulation (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Gehring & Knight, 2000; Kerns et al., 2004). An electrophysiological signal associated with this process is the error-related negativity (ERN), a negative polarity wave peaking approximately 100 ms after making an error (Gehring & Willoughby, 2002; Holroyd & Coles, 2002; Yeung, Botvinick, & Cohen, 2004).

Recent analyses using twin data indicate that approximately 47% of the variance in ERN magnitude is due to shared genetic factors (Anokhin, Golosheykin, & Heath, 2008), suggesting that the ERN has trait-like properties. From an individual differences perspective, a larger ERN should reflect improved action monitoring and more effective engagement of top-down cognitive-control mechanisms in the PFC (Hester, Fassbender, & Garavan, 2004; Pailing, Segalowitz, Dywan, & Davies, 2002). Improved PFC function, in turn, relates to a greater capacity for control (Kane & Engle, 2002; Miller, 2000), allowing for the top-down regulation of ongoing behavioral processes. Differences in the ability to monitor performance and engage these control mechanisms when needed, as reflected by the ERN, should theoretically relate to important self-regulatory differences. Indeed, larger ERNs correlate with reduced impulsivity (Potts, George, Martin, & Barratt, 2006) and improved emotional regulation (Compton et al., 2008). Over time and across a large number of situations, differences in the ability to monitor and regulate one's behavior can potentially manifest themselves in a variety of different life outcomes (Barkley, 2001; Carver & Scheier, 1998; Robinson, 2007).

In the current study, we examined the real-world consequences of effective performance monitoring by correlating the magnitude of the ERN with undergraduate academic performance. It was hypothesized that a greater ability to recruit cognitive-control processes, as reflected in a larger ERN, would be associated with better academic performance.

Method

Participants

Participants were 31 undergraduate students at the University of Toronto Scarborough (14 female). Right-handed participants were selected to avoid physiological differences due to brain laterality. The average age was 19.45 ($SD = 3.08$, range = 18 to 33).

Procedure

Participants completed an informed consent form, along with a demographics questionnaire detailing their age, gender, and the number of years they had been speaking English. Electrophysiological responses were then measured via electroencephalogram (EEG) as participants completed a standard color-naming Stroop task. Color words were presented in colors that either matched or conflicted with the semantic meaning of the words.

Grants from the Social Science and Humanities Research Council and from the Canada Foundation for Innovation supported this research.

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Participants were instructed to press one of four colored buttons on a response box that corresponded to the font color of the stimulus word (red, green, blue, or yellow). Each word appeared for 200 ms, with a maximum response window of 800 ms. An inter-trial interval of 1000 ms was used. A practice session preceded 5 blocks of 48 trials each (32 congruent, 16 incongruent).

Students granted us permission to access their academic transcripts during the consent process. Official transcripts were obtained from the Office of the Registrar, and all identifying information was removed prior to data analysis. All students had completed at least one year of studies, with a mean of 11 courses completed ($SD = 6.47$). Academic performance was quantified as the average numeric course grade earned across all courses, as indicated by official transcripts. This measure of performance was used in all subsequent analyses. To ensure that this variable was not confounded by differences in course difficulty, we examined the relationship between the average difficulty of a student's classes (as reflected in the mean of his or her course averages) and the academic performance variable described above. No relationship was found between these variables, indicating that differences in course selection were not significantly influencing the obtained performance measure.

Electrophysiological processing. EEG was recorded from 32 Ag/AgCl sintered electrodes in a stretch-lycra cap. Vertical eye movements (VEOG) were monitored via a supra- to sub-orbital bipolar montage. EEG and VEOG recordings were digitized at 560 Hz using ASA acquisition hardware (Advanced Neuro Technology B.V., Enschede, Netherlands) with average-ear references and a forehead ground. Electrode impedances were kept below 5 kΩ for all recordings. EEG was corrected for VEOG artifacts using the SOBI procedure (Tang, Liu, & Sutherland, 2005). Frequencies below 1 Hz and above 15 Hz were digitally filtered (96 dB, zero-phase shift). The signal was baseline corrected by subtracting the average voltage occurring 400 to 200 ms pre-response. Movement artifacts were detected with a -75 μV and $+75$ μV threshold. Correct and incorrect trials were averaged separately with an epoch from 200 ms pre-response to 800 ms post-response. ERNs were quantified as the peak minimum deflection between 50 and 150 ms post-response at the frontal midline electrode (Fz).

Results

As predicted by models of self-regulation and cognitive control, academic performance was correlated with ERN magnitude, with better grades being associated with stronger (more negative) ERN responses, $r = -.40$, $p < .05$ (see Figure 1 for scatter plot). This correlation was significant despite statistically controlling for the effects of participants' gender, age, and experience with the English language. A bootstrapped correlation analysis using 10,000 samples computed a 95% confidence interval ranging from -0.13 to -0.60 ($SE = 0.12$), indicating that the effect was not driven by outlying values. Similar results were obtained when analyzing the difference wave between correct and incorrect trials ($r = -.37$) or using the mean rather than minimum voltage between 50 ms and 150 ms post-response on error trials ($r = -.34$). The magnitude of the ERN was thus significantly associated with academic performance, and this effect was relatively stable across different methods of calculating the ERN.

Post-error slowing was used as a behavioral indicator of cognitive control, calculated by subtracting each participant's average reaction time on post-correct trials ($M = 539$ ms, $SD = 56$ ms) from the average reaction time on post-error trials ($M = 556$ ms, $SD = 68$ ms) – the average reaction time across all trials was 540 ms ($SD = 56$ ms). As expected, reaction times following errors and correct trials were significantly different from each other, $t(30) = 2.46$, $p < .05$. In keeping with cognitive models of self-regulation, a larger ERN was associated with increased post-error slowing, $r = -.47$, $p < .05$, theoretically reflecting the engagement of cognitive-control processes in the PFC following errors (Gehring & Knight, 2000). This post-error slowing was in turn associated with higher grades, $r = .42$, $p < .05$. A mediation analysis using the product of coefficients method recommended in MacKinnon, Lockwood, Hoffman, West, and Sheets (2002) confirmed that post-error slowing mediated the relationship between ERN size and academic performance ($z' = 1.68$, $p < .01$). Overall accuracy rates for the Stroop task ranged from 81% to 98% ($M = 91.7\%$, $SD = 4.3\%$), but these rates did not significantly differ between post-error ($M = 92.4\%$, $SD = 8.2\%$) and post-correct ($M = 91.6\%$, $SD = 4.5\%$) trials. No relationship was found between Stroop error rates and the ERN or GPA. Table 1 displays a summary of the obtained correlations.

Headmaps of the ERN revealed the expected frontocentral spatial distribution (see Figure 2). A *single equivalent current dipole* model of the post-error ERPs identified a dorsal ACC source (PAN coordinates [mm]: x = 12.7, y = -3.3, z = 37.2; dipole strength = 54.74 nAm), accounting for 98.4% of the signal variance. Although EEG lacks spatial precision, the obtained source in the dorsal ACC implicates the cognitive aspects of ACC function (as opposed to the more rostral, emotional aspects; Bush, Luu, & Posner, 2000).

Discussion

Academic performance is a gateway to many important life outcomes, influencing the career options that are available to a student. At the broader societal level, achievement in academic domains plays a vital role in sustaining cultural and scientific innovation. The current study suggests that individuals who are better able to monitor their performance and engage cognitive-control mechanisms when needed enjoy greater success in undergraduate programs. It further suggests that the ERN can potentially be employed as a neural marker of this ability.

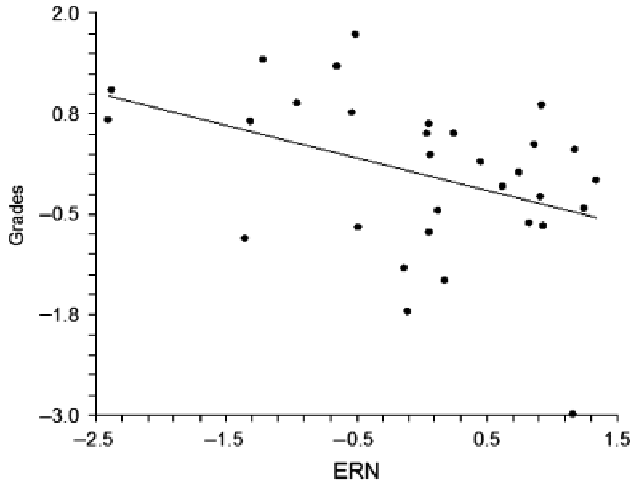

Figure 1. Scatter plot of student grades and ERN magnitude. Both scales reflect z-scores of the variables.

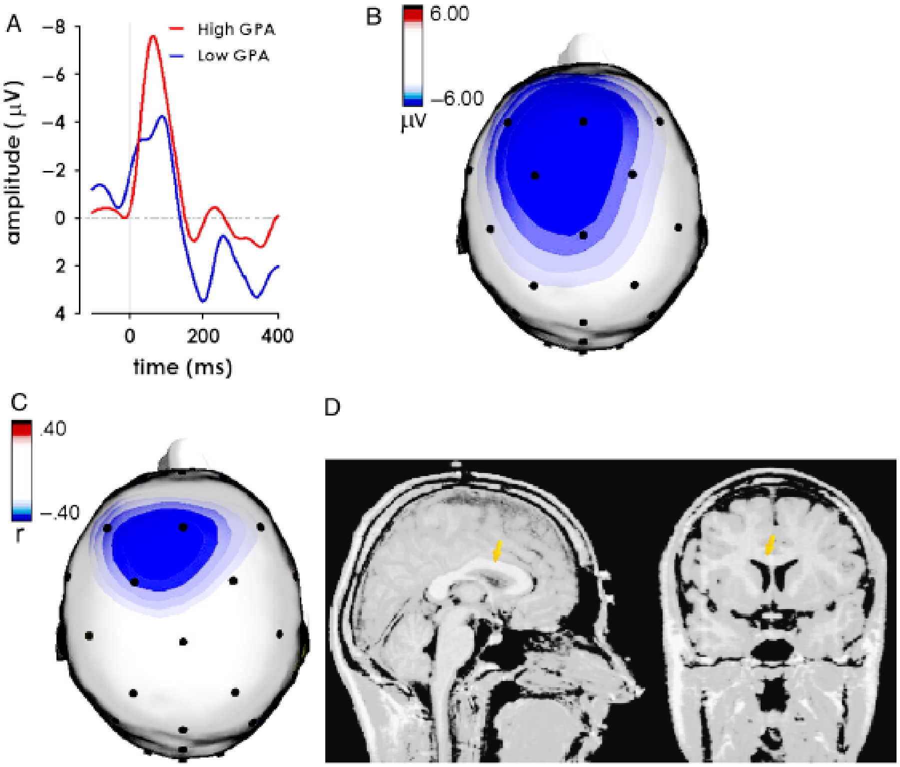

Figure 2. The relation between academic success and the ERN. (A) Event-related potentials at Fz on error trials for individuals with high and low Grade Point Averages, as derived from a tertiary split of the sample. (B) Spatial distribution of the ERN, quantified as the peak minimum voltage deflection occurring between 50 and 150 ms after an error. (C) Headmap of correlations between GPA and ERN magnitude. (D) Source localization indicates an anterior cingulate generator for the ERN.

The current results are in keeping with previous research linking the ERN to self-regulatory processes. For instance, a larger ERN has been associated with better stress regulation (Compton et al., 2008), reduced impulsivity (Potts et al., 2006; Ruchsow, Spitzer, Grön, Grothe, & Kiefer, 2005), and a lower incidence of externalizing disorders (Hall, Bernat, & Patrick, 2007). Given that the ERN appears related to the engagement of self-regulatory control systems, its relationship with academic performance may come as no surprise. Indeed, self-regulatory processes are thought to play an important role in the maintenance of academic goals (Covington, 2000; Pintrich & De Groot, 1990).

It is important to note that, while the magnitude of the ERN is substantially heritable, approximately half of the variance is accounted for by environmental factors (Anokhin et al., 2008). Thus, while ERN size is related to academic performance, it does not necessarily reflect an immutable cognitive ability. It is certainly possible that the engagement of cognitive-control mechanisms associated with the ERN can be improved through training, something that should be explored in future research.

Table 1. *Correlations Between ERN, Grades, Post-Error Slowing, and Stroop Errors*

	ERN	Grades	PES
Grades	– .40*	–	
PES	– .47*	.42*	–
Errors	.03	.07	– .24

*$p < .05$, two-tailed. PES = Post-Error Slowing; Errors = Number of errors on Stroop task.

On a related note, it is not yet clear how the ERN is related to general mental ability, which is one of the most effective predictors of academic performance (Higgins, Peterson, Lee, & Pihl, 2007; Neisser et al., 1996). One possibility is that some of the variance captured by the ERN overlaps with standard tests of intelligence, potentially explaining the observed association with academic performance. Contrary to this explanation, however, is the fact that performance on intelligence tests is related more to lateral PFC activity (Duncan et al., 2000; Gray, Chabris, & Braver, 2003), whereas the ERN is associated with ACC activity (Botvinick et al., 2001; Kerns et al., 2004). Although these brain regions interact, they appear to support two distinct aspects of cognitive control, with the ACC serving an evaluative function which can then signal the need for strategic, executive processes in the lateral PFC.

An implication of this dissociation between the evaluative and executive components of cognitive control is that these systems might interact to predict performance outcomes. It is possible, for instance, that intelligence would moderate the relationship between the ERN and academic performance, such that engaging the cognitive-control systems of the lateral PFC would only lead to performance improvements when enough cognitive resources were available for deployment. An error-monitoring system would be unlikely to predict performance outcomes if there were insufficient cognitive resources for making behavioral corrections after error detection.

An alternative interpretation of the current results is that the ERN may be reflecting increased motivation to perform well on the task, rather than the capacity to engage cognitive-control mechanisms. Indeed, previous research has found that increasing the motivational salience of a task leads to larger ERN magnitudes (Hajcak, Moser, Yeung, & Simons, 2005). Individuals who display a larger ERN on the Stroop task may attain better grades because their motivation levels are generally higher, making them more likely to engage cognitive-control mechanisms and adjust their behavioral responses following errors. This view is supported by research in which highly conscientious individuals were more likely to demonstrate a consistently large ERN, whereas less conscientious respondents only displayed a large ERN when additional monetary incentives were provided to motivate accurate performance (Pailing & Segalowitz, 2004). Importantly, conscientiousness is the best personality predictor of academic achievement, independent of cognitive ability (Higgins et al., 2007; Poropat, 2009), and is also related to higher overall levels of performance motivation (Judge & Ilies, 2002). It is thus possible that the size of the ERN is reflecting some of the performance motivation associated with conscientiousness, which would explain the observed relationship with academic outcomes. Future research could expand on these possibilities by separately examining the contributions of cognitive, motivational, and personality factors.

It should also be noted that while larger ERN responses were associated with improved performance outcomes in the population examined in the current study, large ERNs are sometimes associated with dysfunctional behavior. In particular, large ERNs have been previously associated with anxiety, especially among clinical populations (Olvet & Hajcak, 2008). It is thus possible that larger ERNs may not always reflect improved self-regulation and performance, particularly at the high ends of the distribution. There may instead be an inverse U-shaped relationship with performance, much like the classic theory of optimum arousal (Yerkes & Dodson, 1908).

While the current study provides a promising first inquiry into this topic, further research is needed to more clearly specify the relationship between ERN magnitude, behavioral indicators of cognitive control, and academic performance. In particular, future studies would benefit from using larger sample sizes. The sample size used in the current study is comparable to those used in previous ERN studies, but larger samples would allow for more detailed statistical analyses, including a closer look at potential moderating variables that had somewhat restricted range in this sample (e.g., age and gender). Similarly, while the obtained confidence intervals for the correlation between the ERN and academic performance did not approach zero, a larger sample would help to provide a narrower estimate of the true effect size, as the obtained intervals span a moderately large range.

Overall, the current study provides further evidence for the real-world importance of effective performance monitoring. The pursuit of academic goals requires the continual self-regulation of learning, motivation, and cognitive effort. Individual differences in the extent to which self-regulatory resources can be mobilized in response to errors appear to be an important predictor of success in this domain.

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(Received February 5, 2009; Accepted March 5, 2009)