



## Early math and reading achievement are associated with the error positivity



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### ABSTRACT

Executive functioning (EF) and motivation are associated with academic achievement and error-related ERPs. The present study explores whether early academic skills predict variability in the error-related negativity (ERN) and error positivity (Pe). Data from 113 three- to seven-year-old children in a Go/No-Go task revealed that stronger early reading and math skills predicted a larger Pe. Closer examination revealed that this relation was quadratic and significant for children performing at or near grade level, but not significant for above-average achievers. Early academics did not predict the ERN. These findings suggest that the Pe – which reflects individual differences in motivational processes as well as attention – may be associated with early academic achievement.

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## 1. Introduction

### 1.1. Academics and ERPs

Error-related ERPs, such as the error-related negativity (ERN) and error positivity (Pe), are sensitive to a range of individual differences in both young children and adults, including executive functioning (EF) and motivation. The ERN is thought to index cognitive control and EF processes (e.g., Gehring et al., 1993), while the Pe reflects individual differences in motivational beliefs and values associated with achievement as well as attention (Kim et al., under review; Nieuwenhuis et al., 2001). Behavioral studies have demonstrated links between both EF and motivation and academic achievement, but the nature of these relations has not yet been elucidated in younger populations from an electrophysiological

perspective. The purpose of the present study is to address this research gap by exploring whether early academic skills contribute to variability in these ERP components.

### 1.2. Executive functioning and the ERN

EF – also known as cognitive control – comprises a set of processes that are important for complex, goal-directed behavior (e.g., Best and Miller, 2010). EF is related to growth in math, emergent literacy, and vocabulary in prekindergarten and kindergarten (McClelland et al., 2014), and self-regulation is a unique predictor of early academic outcomes even after controlling for general intelligence (Blair and Razza, 2007; McClelland et al., 2007). Attention skills, a component process of EF, is among the most reliable predictors of later academic achievement in a longitudinal investigation (Duncan et al., 2007), and selective attention is also related to early language, literacy, and math skills (Stevens and Bavelier, 2012). These findings demonstrate that EF skills in early childhood influence academic achievement and growth.

Response monitoring processes are closely related to EF. Being able to select and execute responses in challenging situations is a hallmark of EF skills. When EF skills break down, the need to resolve conflict due to erroneous responses arises. The error-related negativity (ERN) is an ERP component that is elicited when an individual makes a mistake on a speeded target discrimination task, and is thought to reflect error detection and conflict resolution

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processes associated with monitoring one's responses (Falkenstein et al., 1991; Gehring et al., 1993; see Gehring et al., 2012, for a review). Evidence suggests that the ERN is sensitive to development, such that older individuals exhibit a larger ERN (e.g., Davies et al., 2004; DuPuis et al., 2015). A larger ERN is positively associated with undergraduate student grades; stronger grades may be linked to a greater ability to monitor one's performance and engage cognitive control mechanisms (Hirsh and Inzlicht, 2010).

### 1.3. Motivation and the Pe

Hirsh and Inzlicht (2010) speculate that their findings may not simply be due to better EF skills but rather increased motivation to do well on academic tasks. Recent research suggests that individual differences in motivation as a trait-like characteristic may be more closely related to the error positivity (Pe) than the ERN (Moser et al., 2011; Schroder et al., 2014). The Pe reflects the conscious awareness of and increased attention allocated to an erroneous response (Nieuwenhuis et al., 2001; Overbeek et al., 2005). While evidence suggests that the Pe is not sensitive to age (e.g., Davies et al., 2004), recent empirical work indicates that the Pe is sensitive to age-related change during the transition to school period, such that older children exhibit a larger Pe (Grammer et al., 2014). Motivational beliefs and values, including one's perceived competence as well as the value one places on a challenging activity, are also related to the Pe (Kim et al., under review). Increased motivation is related to better academic achievement, even after controlling for prior performance (Wigfield and Eccles, 2000). These findings suggest that the Pe, which indexes motivational processes related to achievement, might be related to actual measures of academic skills.

One theory of the Pe posits that there are two subcomponents, the later of which (the so-called late Pe) is actually a P300 (or P3b) to the erroneous response (Arbel and Donchin, 2009; Ridderinkhof et al., 2009), suggesting that both components may share a common neural basis and functional significance. Consistent with our hypothesized link between the Pe and academic achievement, a larger P300 response has been shown to be related to stronger math and reading achievement in a group of school-aged children (Hillman et al., 2012). The P300 is an ERP component related to one's expectations of events as well as processes associated with attention and updating of working memory (Donchin, 1981; Polich, 2007). We might therefore expect that academic skills would also be related to the Pe.

### 1.4. Aims and hypotheses

The present study seeks to extend our knowledge of the relation between academics and ERPs by exploring whether early academic skills can help to explain the variability in error-related ERPs. While previous research has framed this question by using ERPs as predictors to explain academic outcomes, these studies focused on adults (Hirsh and Inzlicht, 2010) and older children (Hillman et al., 2012), populations in which the ERPs are more stable and better understood. Conceptualizing our study with ERPs as the dependent variable allows us not only to explore the main question regarding the relation between academics and ERPs, but also to address an important fundamental question regarding the sources of variability in the ERN and Pe in young children where the functional significance of these components is still under considerable debate. Our overarching hypothesis was that individual differences in early academic skills would explain a significant portion of the variance in the ERN and Pe, error-related ERP components associated with EF and motivational processes. Specifically, given research demonstrating that the ERN is related to better academic performance in college, we also predicted that better academics would be associ-

ated with a larger ERN in young children. We also explored whether early reading and math achievement might explain variance in the Pe, a component related to individual differences in motivational beliefs and values in young children. Given findings linking the P300 with reading and math achievement, we predicted that stronger academic skills would be related to a larger Pe.

## 2. Method

### 2.1. Participants and procedure

Children were recruited and assessed through two separate but complementary brain-behavior studies – a laboratory-based study and a school-based study. Informed consent and child assent were obtained from parents and their children prior to data collection. The analysis included 113 children between three and seven years of age ( $M = 5.71$ ,  $SD = 0.84$ , Range = 3.43–7.50), with 65 boys and 48 girls. 50 children were from the lab study and 63 children were from the school-based study. There were 28 preschool children, 49 kindergarten children, and 36 children enrolled in first grade at the time of assessment. Reflecting the communities from which the samples were recruited, the majority of children were Caucasian (84 children, 74.3%); six children were Asian, three children were African American, two children were American Indian or Alaska Native, and 18 parents did not provide race/ethnicity information. Eight-eight parents (77.9%) reported highest educational attainment of a college degree (or equivalent) or higher. Parents reported a wide range of household incomes; 38 parents (33.6%) reported yearly incomes of less than \$50,000, 30 parents (26.5%) between \$50,000 and \$100,000, and 44 parents (38.9%) above \$100,000, with one parent not providing this information. Procedures used in the school study are described in Grammer et al. (2014), and the lab-based study is described in Kim et al. (under review).

### 2.2. Academic assessment

Math and reading skills were measured using the Woodcock Johnson III Tests of Achievement letter-word identification and applied problems subtests, respectively (Woodcock et al., 2001). Both tests have been normed and validated and used extensively in preschool and school-aged children. The letter-word subtest assesses identification and pronunciation of letters and words, while the applied problems subtest includes math and counting problems presented orally.

### 2.3. Task

Participants played a child-friendly Go/No-Go task called the Zoo Game (Grammer et al., 2014; Lamm et al., 2014; McDermott et al., under review). In the game, children were told that someone had let all the animals out of their cages, and that it is the child's job to help the zookeeper put all the animals back in their cages by pressing a button on a response device. The children were told that they would have three orangutan assistants who would help them catch the animals. Children were shown pictures of each of the three orangutans and were told to remember them and not to capture them because they are helping. Therefore, the No-Go stimuli were the three orangutans and the Go stimuli were all the other animals. Sample images from the Zoo Game are presented in Fig. 1.

The Zoo Game was presented using EPrime 2.0 (Psychology Software Tools, 2010) on a 22-in. Asus LCD monitor. Each trial started with the presentation of a fixation cross for 300 ms, then an image of an animal (the stimulus) for 750 ms, and a blank, black screen for 500 ms. The ratio of Go to No Go trials was 3:1, with 30 Go animals

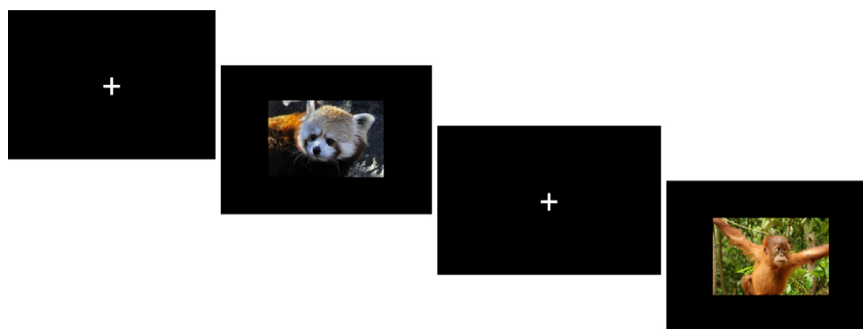


Fig. 1. Sample images from the Go/No-Go Zoo Game.

and 10 No Go orangutans presented in each of eight blocks. Children were given the opportunity to practice during a practice block consisting of 12 trials with the same ratio of Go to No/Go animals. Responses were registered during image presentation as well as during the blank screen. All images were of the same size and were selected carefully so that the animals were easily identifiable from the background but were not particularly salient for other reasons. This was done in order to prevent children from being particularly drawn to a particular animal because of the image background or other peripheral features. Children in both studies made responses on a standard game controller (Logitech Dual Action Game Pad USB). Both speed and accuracy were emphasized; participants were instructed to catch the animals as fast as possible, with regular reminders not to press the button for the orangutan friends. In order to reduce anxiety and worry, children were reassured that if they accidentally put the orangutans in their cages, their orangutan friends would get free and help them catch the animals again. In order to sustain enthusiasm and task engagement, children were provided with short breaks as necessary and were rewarded with stickers at regular intervals during the testing session.

#### 2.4. Electrophysiological recording

EEG data were acquired using a BioSemi Active Two system using 32 Ag/AgCl electrode caps suitable for young children. A small amount of electrolyte (SignaGel) was applied to the child's scalp at each electrode. Flat electrodes were placed around each child's eye in order to account for the electrooculogram. Electrode offsets were kept between  $\pm 30 \mu\text{V}$ . Reference recordings were acquired by placing flat electrodes at each mastoid location (behind the left and right ears). Data were recorded referenced to a ground formed from a common mode sense (CMS) active electrode and driven right leg (DRL) passive electrode (see <http://www.biosemi.com/faq/cms&drl.htm>).

Offline, all data processing was performed using ERPLAB. EEG data were digitized at 512 Hz and were resampled at 256 Hz after recording. Prior to eye movement correction, data were screened using a programmed set of algorithms that rejected trials that met any of the following three criteria: (1) the absolute voltage range for any individual electrode exceeded  $500 \mu\text{V}$ , (2) a change greater than  $50 \mu\text{V}$  was measured between two consecutive data points, and (3) the data deviated by more than +25 or  $-100 \text{ dB}$  in a frequency window of 20–40 Hz in order to detect and remove muscle artifacts. From the continuous EEG, 1000 millisecond segments were extracted beginning 400 ms prior to correct and erroneous responses. ERP data were corrected for blinks and eye-movement artifacts using the method developed by Gratton et al. (1983). ERP averages were baseline corrected by subtracting from each data point the average activity in a 200 to 100 ms window prior to the response. Each trial was also visually examined for artifacts and rejected if muscle or other artifacts were still present after the

Table 1

Descriptive statistics for academic achievement variables.

Variables	Mean	SD	Median	Range
Letter-word identification (reading)				
Grade equivalent	1.4	1.1	1.0	<0.0–5.4
Age equivalent	79.7	14.6	76	38–129
W score	401.5	46.2	388	305–511
Applied problems (math)				
Grade equivalent	1.5	1.2	1.3	<0.0–4.7
Age equivalent	80.1	15.4	78	55–122
W score	446.7	23.8	444	405–504

Note: Age equivalent score is in months.

automated artifact correction procedure. In the following figures, waveforms were filtered with a nine-point Chebyshev II low-pass, zero-phase-shift digital filter (Matlab R2010a; Mathworks, Natick, MA), with a half-amplitude cutoff at approximately 30 Hz.

The ERN was defined as the mean voltage in the window from 0 to 50 ms (0 ms denoting the response), and the Pe was defined as the mean voltage in the window from 200 to 500 ms; both the ERN and Pe were compared to correct trial activity in the same windows. All ERP components were evaluated along the midline (i.e., FCz, Cz, Pz). Behavioral measures were analyzed using analysis of variance (ANOVA), and all ERP components were statistically evaluated using repeated measures ANOVA with the Greenhouse-Geisser epsilon correction to adjust for violations of the sphericity assumption. Statistical analyses were conducted using Stata 13.1.

### 3. Results

#### 3.1. Academic outcomes

Grade equivalent scores of the Woodcock Johnson academic subtests were used in the present analysis. These scores provide an easily interpretable measure of reading and math achievement through grade level performance. Grade equivalents are derived from the W score (a metric derived from the Rasch model of data analysis), which is on an equal-interval scale and thereby allows us to directly compare the achievement of one student against another, regardless of age (Jaffe, 2009). Children's reading achievement was significantly related to age,  $r=0.71$ ,  $p<0.001$ , as well as math achievement,  $r=0.74$ ,  $p<0.001$ . However, achievement was not related to gender. Descriptive statistics for the academic variables are presented in Table 1.

#### 3.2. Comparisons between study samples

T-tests and chi-square tests revealed that the children in the two studies did not differ on gender, ethnicity, and highest level of parental education. However, children in the school study were significantly older than their peers in the lab study,  $t(111)=-4.90$ ,

**Table 2**  
Behavioral performance on the Zoo Game.

Variables	Mean	SD	Range
Number of correct (Go) trials	209.46	32.15	72–240
Number of error (No-Go) trials	26.45	12.21	6–59
Percent correct (Go trials)	90.10	11.23	35.42–100.00
Percent incorrect (No-Go trials)	34.21	15.43	7.50–81.94
Reaction time (correct trials)	580.18	75.80	402.04–817.10
Reaction time (error trials)	471.51	66.23	337.49–613.95

Note: Reaction time is in milliseconds. Correct trials were defined as the number of correct responses on Go trials, excluding correct non-responses during No-Go trials. Error trials were defined as the number of errors of commission during No-Go trials, excluding errors of omission during Go trials.

$p < 0.001$ . In addition, the school study represented a larger proportion of kindergarten and first grade children, while the lab study represented a larger proportion of preschool children,  $X^2(2) = 36.31$ ,  $p < 0.001$ . These age and grade differences reflect a primarily school-based recruitment strategy in the school study, where kindergarten and first grade children were more likely to be included. In addition, the school study represented a larger proportion of children in the lowest income category (less than \$50,000) compared to lab study children,  $X^2(2) = 14.62$ ,  $p = 0.001$ . This income difference can be attributed to the inclusion of children enrolled in Head Start in the school study. As described below, these demographic differences do not affect the main findings.

### 3.3. ERP behavioral measures

Children's accuracy and reaction time on correct (Go) and error (No-Go) trials are presented in Table 2. Consistent with previous research, children were slower in responding on correct trials compared to error trials; this difference was statistically significant,  $t(112) = 22.84$ ,  $p < 0.001$ . Other measures of action monitoring, such as posterror task performance, were not explored in the current investigation, particularly given the considerable debate regarding the properties and the functional significance of posterror slowing in young children.

### 3.4. Electrode analysis

Negative ERN amplitudes were interpreted as negative polarities; that is, a larger ERN indicates a more negative ERN, and a smaller ERN indicates a less negative ERN. As seen in Table 3, the ERN was maximal at FCz and the Pe on error trials was maximal at

**Table 3**  
Mean amplitudes for ERP components at midline electrode sites.

Variables	FCz	Cz	Pz
ERN	-2.89 (4.73)	-1.44 (4.65)	1.81 (5.27)
CRN	0.96 (3.77)	2.41 (3.62)	0.97 (4.73)
$\Delta$ ERN	-3.86 (5.30)	-3.85 (5.26)	0.84 (6.80)
Pe (error trials)	6.33 (9.10)	9.45 (8.31)	9.13 (9.06)
Pe (correct trials)	7.68 (6.29)	5.36 (5.22)	-4.76 (8.38)
$\Delta$ Pe	-1.35 (7.73)	4.09 (7.67)	13.90 (8.11)

Note: Amplitudes are in microvolts ( $\mu$ V), standard deviations are in parentheses.

Cz. Difference measures were also generated in order to properly account for brain activity occurring during both correct and incorrect responses, thereby producing a measure of activity specific to errors (e.g., Torpey et al., 2011). Because the sample comprised children from two separate studies, difference measures of the ERN and Pe may be less affected by study-specific characteristics. The  $\Delta$ ERN was defined as the brain activity on error trials minus the brain activity on correct trials (often called the correct response negativity, or CRN) in a 0–50 ms window, and the  $\Delta$ Pe was defined as the brain activity on error trials minus the brain activity on correct trials in a 200–500 ms window. The  $\Delta$ ERN was maximal at FCz and  $\Delta$ Pe was maximal at Pz. Consistent with previous research on these components in young children, we focused our analysis at FCz for the ERN and Pz for the Pe.

### 3.5. ERN

Waveforms for response-locked ERPs for correct and error trials are shown in Fig. 2 at midline electrode sites. The ERN was observed as a negative deflection peaking in a window between 0 and 50 ms after the response at frontocentral electrode sites. A 3 (Electrode Site: FCz, Cz, Pz)  $\times$  2 (Trial Type: Correct, Error) repeated measures ANOVA confirmed that there was a main effect of electrode site,  $F(2,560) = 19.17$ ,  $p < 0.001$ ,  $\epsilon = 0.67$ , as well as a main effect of trial type,  $F(1,560) = 53.42$ ,  $p < 0.001$ . The significant interaction between electrode site and trial type suggests that the amplitude difference between correct and error trials varied as a function of electrode site,  $F(2,560) = 25.03$ ,  $p < 0.001$ ,  $\epsilon = 0.68$ . Follow-up post-hoc paired sample  $t$ -tests demonstrated that amplitudes were more negative on error trials compared to correct trials at FCz,  $t(112) = -7.74$ ,  $p < 0.001$ , and Cz,  $t(112) = -7.78$ ,  $p < 0.001$ , but not at Pz,  $t(112) = 1.32$ ,  $p = 0.19$ . The ERN was larger at FCz compared to Cz, providing further evidence that the ERN was maximal at FCz,  $t(112) = -4.10$ ,  $p < 0.001$ . However, when exploring mean

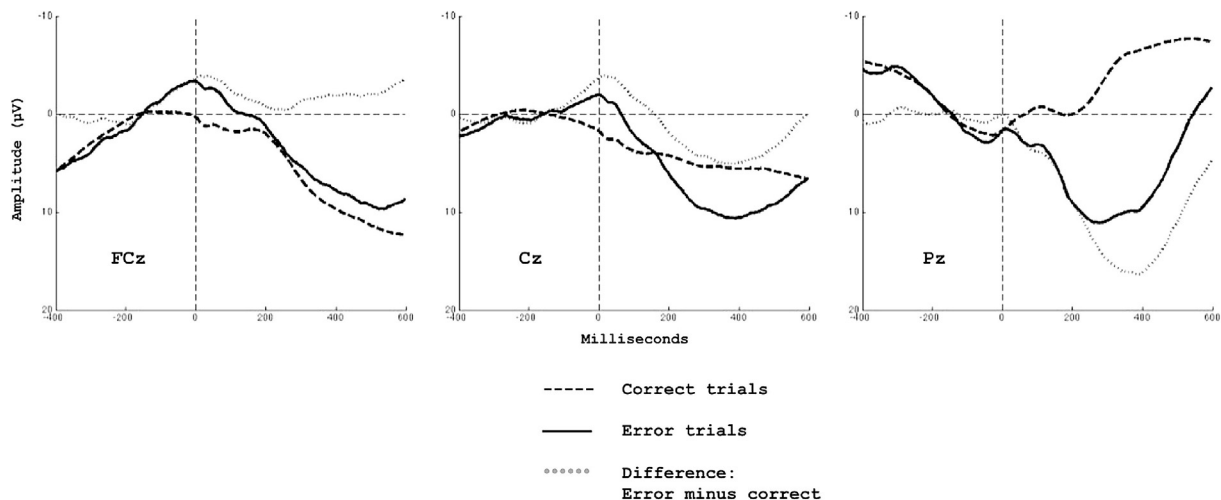


Fig. 2. Grand average waveforms at midline electrode sites. The vertical dashed line at time zero indicates the time of the response (button-press switch closure).



differences between the ERN and CRN, the  $\Delta$ ERN at FCz was not significantly different from the  $\Delta$ ERN at Cz,  $t(112) = -0.01$ ,  $p = 0.99$ .

### 3.6. Pe

The Pe was observed as a slow positive deflection between 200 and 500ms after the response at centroparietal electrode sites. A 3 (Electrode Site: FCz, Cz, Pz)  $\times$  2 (Trial Type: Correct, Error) repeated measures ANOVA confirmed that there was a main effect of electrode site,  $F(2,560) = 43.55$ ,  $p < 0.001$ ,  $\epsilon = 0.61$ , as well as a main effect of trial type,  $F(1,560) = 118.73$ ,  $p < 0.001$ . The significant interaction between electrode site and trial type suggests that the amplitude difference between correct and error trials varied as a function of electrode site,  $F(2,560) = 76.87$ ,  $p < 0.001$ ,  $\epsilon = 0.70$ . Follow-up post-hoc paired sample  $t$ -tests showed that amplitudes were more positive on error trials compared to correct trials at Cz,  $t(112) = 5.67$ ,  $p < 0.001$ , and Pz,  $t(112) = 18.22$ ,  $p < 0.001$ , but were marginally smaller on error trials at FCz,  $t(112) = -1.86$ ,  $p = 0.07$ . Although the Pe at Cz did not significantly differ from the Pe at Pz,  $t(112) = 0.35$ ,  $p = 0.73$ , the Pe was larger at Cz compared to FCz,  $t(112) = -5.10$ ,  $p < 0.001$ , and larger at Pz compared to FCz,  $t(112) = -2.30$ ,  $p = 0.02$ , providing evidence that the Pe was maximal at centroparietal sites. When exploring mean differences between the Pe on error trials and the Pe on correct trials, the  $\Delta$ Pe was larger at Pz compared to Cz,  $t(112) = -12.58$ ,  $p < 0.001$ .

### 3.7. Relation between academics and ERPs

Scatterplots with overlaid linear and quadratic best-fit lines depicting the relation between academics and ERPs are presented in Figs. 3 and 4. The quadratic best-fit lines show that the relation between academics and the ERN and Pe for children performing at or just above grade level (i.e., between preschool and second grade) is positive, whereas the relation for above-average achievers (i.e., approximately second grade level and above) appears to be negative. In addition, the magnitude of the  $\Delta$ ERN is smallest (less negative) and the magnitude of the  $\Delta$ Pe is largest for children performing at the second grade level, where the quadratic curve reaches its peak. Waveforms in Figs. 5 and 6 show that the magnitude of the  $\Delta$ Pe is significantly different for children performing around grade level compared to children performing between the 1.5 and 2.5 grade levels, where the absolute magnitude of the  $\Delta$ Pe is largest.

### 3.8. Multiple regression analysis

Our multiple regression analysis included a set of control variables that may be related to variance in the ERN and Pe. In addition to controlling for age, the grade variable allowed us to test whether the ERPs were sensitive not only to chronological age but also to schooling. We also included gender and study dummy variables; because the children in the present analysis were drawn from two studies, we explored whether there were any unobservable differences between the two groups that may have led to different ERPs. Finally, we also included error rate on the Go/No-Go task as a behavioral proxy of children's EF. We did this in order to explore whether the relation between academics and the Pe was due to behavioral factors related but not identical to achievement. Given visual evidence of a quadratic relation between academics and ERPs, we estimated mean marginal estimates from a quadratic specification in order to confirm whether a non-linear function was indeed the best fit for our data. Because the quadratic specification is robust to linearity, if the underlying relation was in fact linear, this non-linear specification would not change the coefficients (though it is possible that the standard errors would be slightly larger). We found some evidence for a quadratic relation between academics and

**Table 4**  
Mean marginal estimates for  $\Delta$ ERN and  $\Delta$ Pe.

VARIABLES	$\Delta$ ERN (FCz)		$\Delta$ Pe (Pz)	
	(1)	(2)	(3)	(4)
Child age	0.777 (1.289)	0.643 (1.334)	-0.180 (1.870)	-0.020 (1.962)
Kindergarten <sup>a</sup>	1.121 (1.878)	1.019 (1.902)	-2.449 (2.725)	-2.587 (2.796)
First grade <sup>a</sup>	-0.060 (2.772)	-0.397 (2.768)	-4.965 (4.021)	-4.484 (4.070)
Child gender <sup>b</sup>	0.951 (1.074)	1.009 (1.069)	-2.289 (1.558)	-1.681 (1.572)
Study <sup>c</sup>	-0.680 (1.263)	-0.761 (1.271)	-1.506 (1.832)	-1.755 (1.869)
Error rate (percent incorrect) <sup>d</sup>	2.106 (3.451)	2.376 (3.476)	-15.28 <sup>**</sup> (5.006)	-13.48 <sup>**</sup> (5.111)
Reading (grade equivalent)	0.128 (0.895)		3.271 <sup>+</sup> (1.298)	
Math (grade equivalent)		0.380 (0.853)		2.355 <sup>+</sup> (1.254)
Observations	113	113	113	113
R-squared	0.044	0.037	0.142	0.112

Note: Standard errors in parentheses.

<sup>+</sup>  $p < 0.10$ .

<sup>\*</sup>  $p < 0.05$ .

<sup>\*\*</sup>  $p < 0.01$ .

<sup>a</sup> Grade level reference variable is preschool.

<sup>b</sup> Male = 0, Female = 1.

<sup>c</sup> Laboratory-based study = 0, School-based study = 1.

<sup>d</sup> Expressed as a decimal between 0 and 1.

the  $\Delta$ Pe; the quadratic term for the Reading/ $\Delta$ Pe regression was significant ( $p = 0.01$ ), while the quadratic term for the Math/ $\Delta$ Pe regression was not significant ( $p = 0.13$ ).

The results of the multiple regression are presented in Table 4. Four separate regression estimates were computed, two for  $\Delta$ ERN and two for  $\Delta$ Pe, with reading and math separately predicting each ERP variable. Age, grade, child gender, and study were not related to the magnitude of the  $\Delta$ ERN and  $\Delta$ Pe, although we found that a larger error rate (i.e., worse accuracy) predicted a smaller Pe. Neither reading nor math explained any variance in the  $\Delta$ ERN. However, for both reading and math, stronger academic scores were related to a larger  $\Delta$ Pe, holding the other variables constant.

### 3.9. Comparing average versus above-average achievers

The results above suggest that the relation between academics and the  $\Delta$ Pe is non-linear (particularly between reading and the  $\Delta$ Pe), and that reading predicts the magnitude of the  $\Delta$ Pe while the relation between math and the  $\Delta$ Pe is significant at trend level. However, the mean marginal estimates in Table 4 mask important differences between average and above-average achievers. The coefficients in Table 4 represent the mean of all the marginal effects at every point on the quadratic regression curve. Put differently, an increase of one grade level in reading achievement is related, on average, to an increase of 3.271  $\mu$ v in the  $\Delta$ Pe. However, because the relation between academics and the  $\Delta$ Pe is non-linear, this single coefficient oversimplifies the true nature of our data. In order to better understand the nature of this relation, we estimated the marginal effect at different points on the quadratic regression curve to assess where the academics/ $\Delta$ Pe effect is significant and where it is not. This can be accomplished by calculating the slope at different points on the curve by varying the grade equivalent score and holding the values of the other predictors at their means.

Table 5 presents the marginal regression estimates on a range of grade equivalent scores that captured children's actual achievement in both reading and math. The coefficients represent the marginal effect of (or the slope at) a particular grade level on the

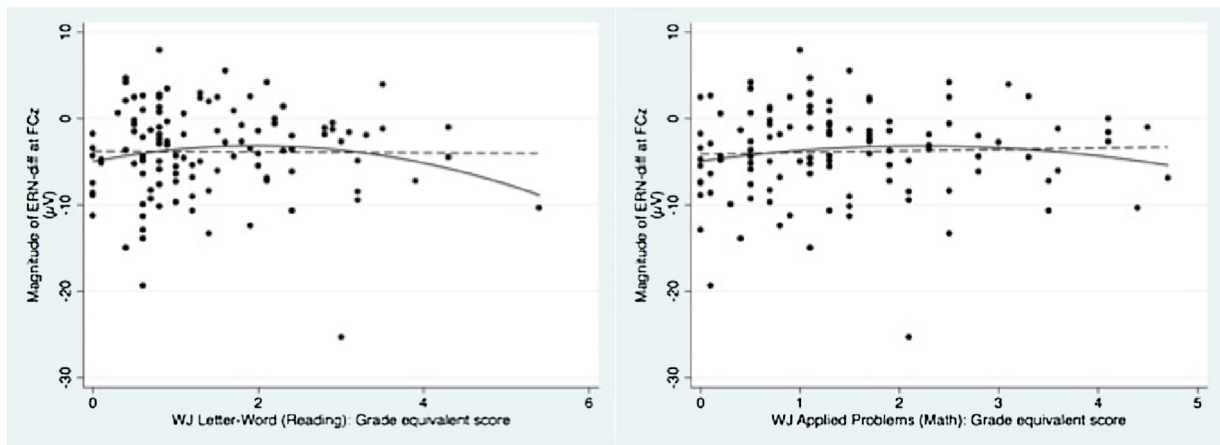


Fig. 3. Scatterplots depicting the bivariate relation between the  $\Delta$ ERN and reading (left panel) and math (right panel). The linear best fit is presented in the dashed line, while the quadratic best fit is represented by the solid line.

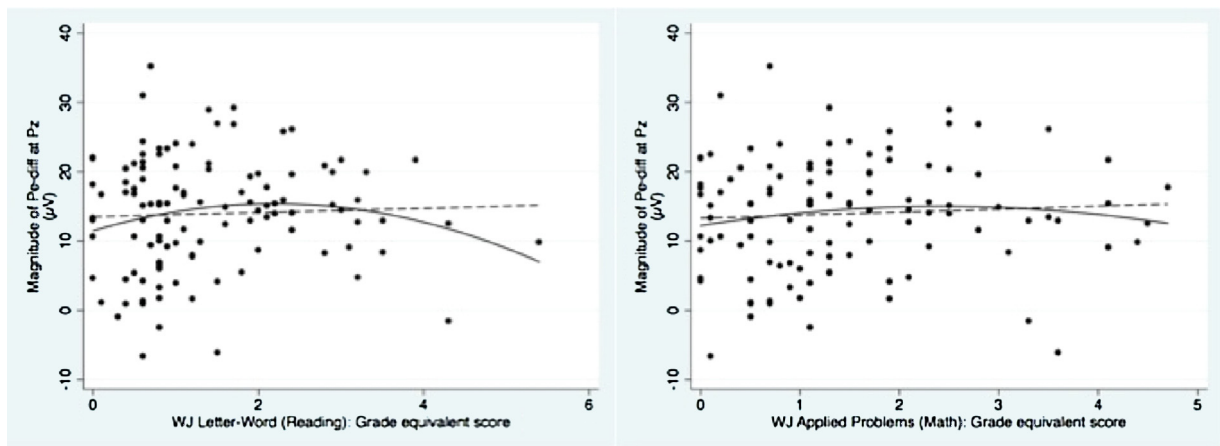


Fig. 4. Scatterplots depicting the bivariate relation between the  $\Delta$ Pe and reading (left panel) and math (right panel). The linear best fit is presented in the dashed line, while the quadratic best fit is represented by the solid line.

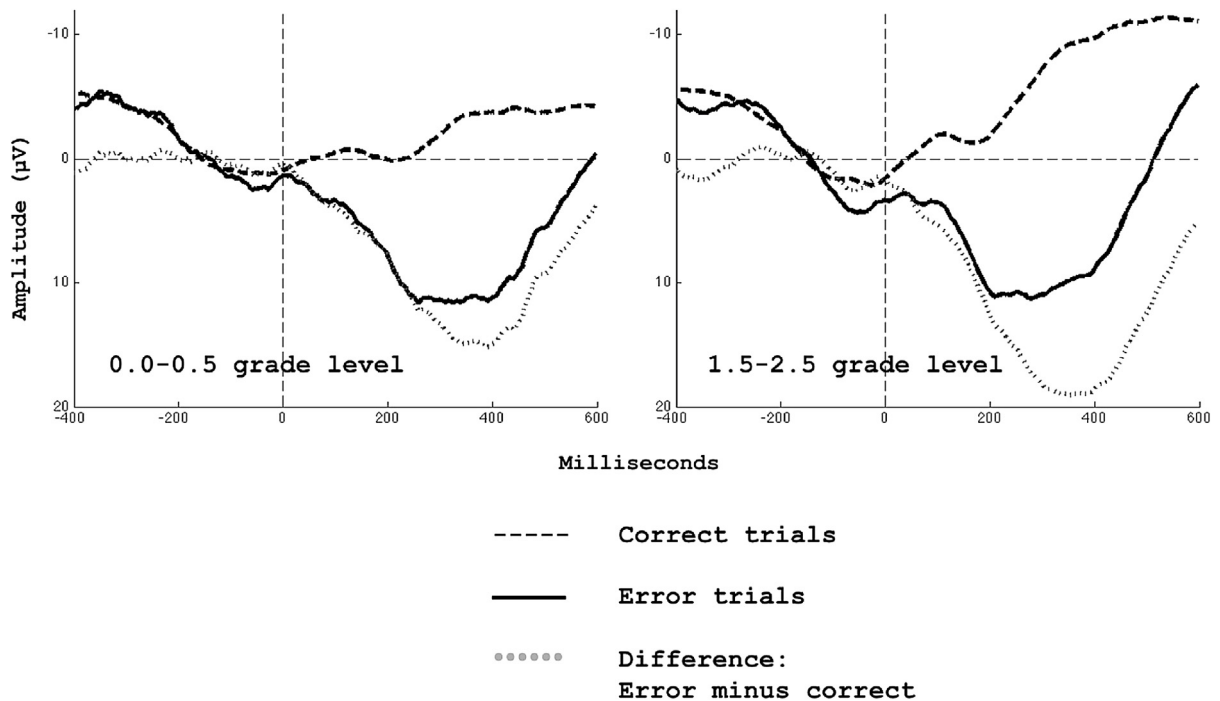
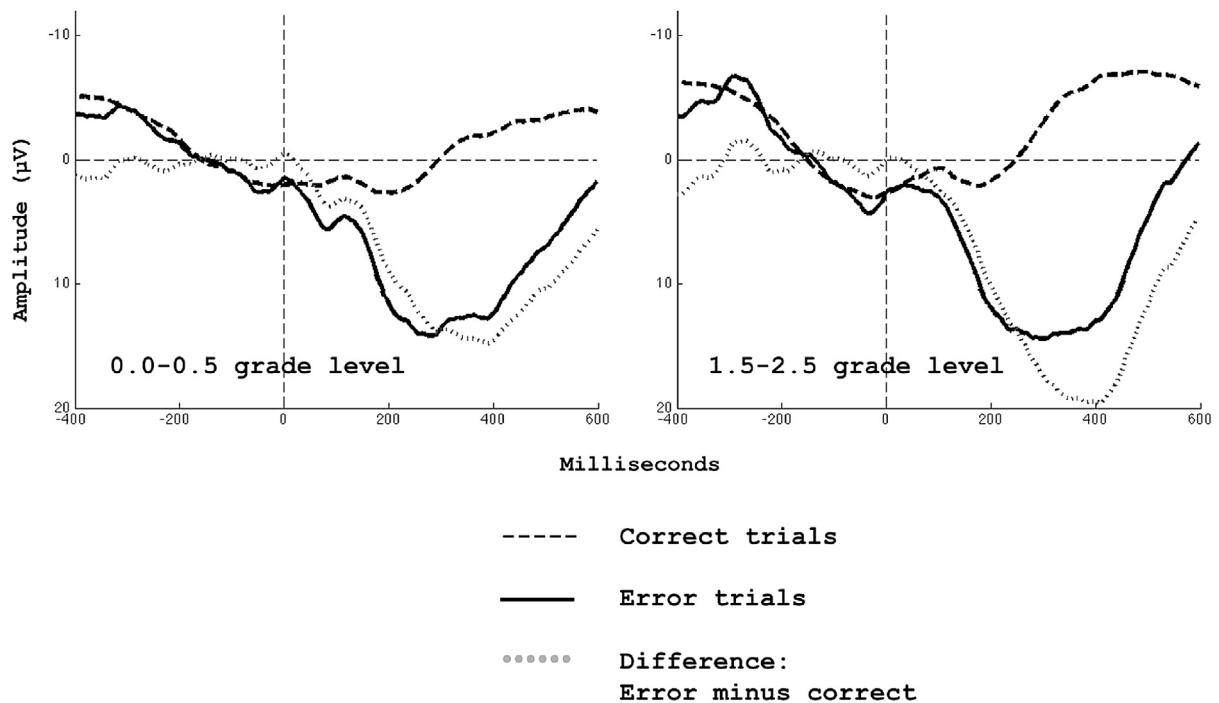


Fig. 5. Waveforms comparing average and above-average readers at Pz. The vertical dashed line at time zero indicates the time of the response (button-press switch closure).



**Fig. 6.** Waveforms comparing average and above-average math achievers at Pz. The vertical dashed line at time zero indicates the time of the response (button-press switch closure).

**Table 5**  
Marginal regression estimates at various grade levels.

Grade level	Reading $\Delta$ Pe (Pz)	Math $\Delta$ Pe (Pz)
0.0	7.040** (2.573)	4.758* (2.561)
0.5	5.702** (2.087)	3.930* (2.069)
1.0	4.363** (1.630)	3.103* (1.610)
1.5	3.025* (1.232)	2.276* (1.222)
2.0	1.687* (0.972)	1.449 (0.992)
2.5	0.348 (0.967)	0.622 (1.031)
3.0	-0.990 (1.220)	-0.205 (1.317)
3.5	-2.328 (1.615)	-1.032 (1.730)
4.0	-3.667* (2.071)	-1.859 (2.200)
4.5	-5.005* (2.556)	-2.686 (2.698)

Note: Standard errors in parentheses.

\*  $p < 0.10$ .

\*  $p < 0.05$ .

\*\*  $p < 0.01$ .

magnitude of the  $\Delta$ Pe. The main conclusion is that at the bottom of the grade level achievement distribution, an increase in reading and math grade level is associated with a fairly large increase in the magnitude of the  $\Delta$ Pe, as shown by the large positive coefficients. However, in the middle of the distribution where the absolute magnitude of the  $\Delta$ Pe is largest, this same increase is associated with a much smaller increase in the  $\Delta$ Pe, as shown by the coefficients approaching zero. For example, when the reading level increases from 0.0 to 0.1, the  $\Delta$ Pe increases by  $0.704 \mu\text{V}$ , but when the reading level increases from 2.0 to 2.1, the  $\Delta$ Pe increases by just

$0.169 \mu\text{V}$ . That is, the marginal effect of grade level becomes smaller as you go up the grade level distribution. This is exactly what we observe in the scatterplots in Figs. 3 and 4.

Three other conclusions can be drawn. First, the relation between academics and the  $\Delta$ Pe is significant only for children performing at or just above grade level. Specifically, the relation between reading and the  $\Delta$ Pe is significant only for children reading at a second grade level or below, while the relation between math and the  $\Delta$ Pe is significant at trend level for children doing math at a 1.5 grade level or below. Second, within this group, the academics/ $\Delta$ Pe effect appears to become less positive as children increase in grade level achievement. However, we cannot conclude that these coefficients are significantly different from each other due to the fairly large standard errors. Third, there is no clear effect for the above-average achievers. The coefficients turn negative, suggesting that the academics/ $\Delta$ Pe effect may go in the opposite direction for these higher achievers, but this finding is not statistically significant. There is a significant result for children who read at a fourth grade level and above, but because there are so few children who actually performed so highly ( $N=3$ ), this finding likely does not have much generalizability.

#### 4. Discussion

The purpose of the present study was to better understand error-related ERP components in young children through the lens of early academic achievement. We speculated that early academic achievement might help to explain the variance of the ERN and Pe, given links between these components and measures of EF and motivation, respectively. While neither reading nor math predicted the magnitude of the ERN, stronger achievement in both academic domains did predict a larger Pe. Moreover, we found some evidence that the relation between academics and the Pe was non-linear in nature, and that this association was limited to children performing at or near grade level.

#### 4.1. Academics are related to the Pe but not the ERN

Our results are consistent with previous empirical work linking the Pe, but not the ERN, to behavioral variables associated with achievement. The Pe is linked to trait-like motivational beliefs and values in young children (Kim et al., *under review*); the results presented here suggest that strong academic achievement is related to electrophysiological processes associated with motivation. Recall that the Pe is also thought to reflect attention to the erroneous response, which is significant because attention is an important component process of EF. Therefore, our results also indicate that one aspect of EF in particular – attention – is sensitive to academic achievement, at least when these processes are explored from an electrophysiological perspective.

While previous work has found an association between academics and the ERN, that study focused on a college-aged sample (Hirsh and Inzlicht, 2010). The present findings therefore indicate that the relation between academics and ERPs may depend on development, and that academic skills may have different effects depending on the particular aspect or stage of error processing being explored. Early academic skills may be more closely related to neural correlates underlying beliefs and values about achievement, while success in later schooling may be more dependent on neural correlates of EF skills and cognitive control processes, over and above the role of attention.

#### 4.2. Differences between lower and higher achieving children

The relation between reading and math and the  $\Delta$ Pe was significant only for the children performing at or just above grade level. It is important to note that the average reading and math grade equivalent scores were 1.4 and 1.5, respectively, while the average age of our sample was 5.71 years, suggesting that the children in our study were higher-than-average achievers. As mentioned above, the coefficients indicate that the academics/ $\Delta$ Pe effect may be negative, not positive, for the above-average achievers. There are two possible reasons why we failed to see a significant effect for these children. It is possible that these higher achievers have noisier data that make it difficult to detect a significant effect. We can rule out this possibility because the standard errors are similar for average and above-average achievers. The more likely explanation is that the very small sample size at the top of the grade level distribution makes it difficult to detect an effect if there really is one. Therefore, we are unable to reject the null hypothesis that there is no relation between academics and the  $\Delta$ Pe for the higher achievers.

Why would the relation between academics and the Pe not hold for very high achievers? If we understand the Pe as being sensitive to individual differences in trait-like motivational processes associated with achievement, our results suggest that there might be a ceiling effect of motivation. In particular, higher levels of academic achievement are related to higher levels of motivation, but only to an extent. In our study, this relation appears to hold only for children performing at or just above grade level in reading and math. Our findings also point to the possibility that better academic performance may increase one's motivation to learn and succeed in school and to pay attention, although the converse may also be true. This interpretation would have important implications in how educators promote achievement and positive motivational processes. Our exploration of the electrophysiological correlates of motivation in young children, rather than using behavioral data alone, allows us to better understand the relation between academics and motivation.

Finally, it should be noted that our observation of non-linearity between academic skills and the Pe was statistically significant only for reading. Although there was visual evidence of non-linearity for

math, the quadratic term was not significant at conventional levels. While it is unclear as to why we would observe a non-linear relation for reading but not for math, it is likely that the true functional form between both academic skills and the Pe is indeed non-linear rather than linear for two reasons. First, given the significance level for the quadratic term for math ( $p = 0.13$ ), it is possible that a larger sample size would sufficiently reduce the standard error for the term to reach significance. Second, the marginal regression estimates at various grade levels show a very similar pattern for both reading and math (e.g., decreasing effects as a function of grade level, region of significance only at the lower end of the academic distribution, etc.), suggesting that both academic domains share the same non-linear pattern even if it is only statistically significant for reading. Future research is needed to replicate and extend these preliminary findings.

#### 4.3. Motivation or attention?

Our finding that stronger academic skills are related to a larger Pe is significant, given that the Pe is related to attentional processes as well as individual differences in motivation. The question arises as to whether motivational and attentional processes should be understood as being mutually exclusive, or whether motivation and attention share a common underlying factor, at least in young children. Evidence suggests the latter explanation. The achievement goal theory of motivation argues that goal orientations are associated with different patterns of divided and undivided attention to tasks and goals (Dweck and Leggett, 1988). In an empirical investigation, mastery-oriented children exhibited quicker and more accurate performance on tasks that required attention compared to performance-oriented children (Chang and Burns, 2005). The stimulus-locked P300 or P3b, which shares a common neural basis and functional significance with the response-locked Pe (specifically, the so-called late Pe), is related to attentional processes, particularly when accuracy is emphasized over speed (Arbel and Donchin, 2009). Such findings from behavioral and electrophysiological investigations suggest that the Pe may indeed index both motivational and attentional processes, although the relative contribution of each is still unknown.

#### 4.4. Limitations and directions for future research

There are several limitations of the present study that future investigations should address. First, protocol differences across the two studies precluded us from systematically exploring whether other demographic variables might help to explain the variance in the ERN and Pe. Because achievement has been associated with socioeconomic status (SES), not controlling for SES might overstate the relation between academics and ERPs. The school study did have a larger proportion of families whose children were enrolled in Head Start. However, note that we did include a study dummy variable in our regression analysis, and this variable was not significantly related to the ERN or Pe. Nevertheless, this dummy variable is at best an imperfect proxy for SES. Second, the study would have been strengthened by inclusion of behavioral assessments of executive functioning and motivation rather than relying on electrophysiological measures alone. Although we used error rate on the Go/No-Go task as a behavioral proxy for EF, other EF and motivation assessments might have provided additional insights into the relation between academics and ERPs. Employing a multi-method and multi-assessment approach would help us better understand the observed phenomena. Future research should also explore whether our Pe results are due to motivational processes or attentional skills. Videotaped coding of participants as they engage in behavioral tasks and ERP recording would provide more information regarding the extent to which children are



paying attention to the experimental tasks, allowing us to potentially disentangle motivational and attentional effects. Third, due to the cross-sectional nature of our data and our research design, we could not make any causal claims that individual differences in academic skills are causally linked to ERPs, or vice versa. Using quasi-experimental approaches and experimental methods may have the potential to unlock a greater understanding of the causal link between academics and ERPs.

#### 4.5. Conclusion

This study explored whether early academic achievement is useful in better understanding the nature of electrophysiological correlates underlying executive functioning and motivation. We found that early reading and math achievement were each related to the magnitude of the Pe, such that better academics predicted a larger Pe. This suggests that variability in the Pe is explained at least in part by early academic achievement, and we speculate motivational processes indexed by the Pe – such as beliefs and values about achievement – as well as attentional processes, might explain this relation. This study adds to the growing literature demonstrating that individual differences in motivation and achievement contribute to variability in error-related ERPs, particularly the error positivity, in young children.

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