Motivation and error processing during the transition to school

by

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"For today, goodbye; for tomorrow, good luck; and forever, GO BLUE!"

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## Abstract

In this dissertation, the event-related potential technique is used to explore specific patterns of brain responses associated with error processing and cognitive control – namely, the error-related negativity (ERN) and error positivity (Pe) – as a way to better understand the nature of EF and motivation in young children. In the first study, the links between children's perceived competence and intrinsic task value beliefs on the ERN and Pe were explored, as well as children's temperamental levels of anger/frustration, an important achievement-related emotion. Individual differences in motivation were not related to the ERN. However, stronger perceived competence beliefs were related to a larger Pe, whereas stronger intrinsic task value beliefs predicted a smaller Pe. Higher temperamental levels of anger/frustration were related to a larger Pe. In the second study, a regression discontinuity design was used to explore whether early schooling has unique effects on children's early reading and math outcomes, behavioral measures of inhibitory control, and electrophysiological measures related to EF and motivation. Kindergarten schooling uniquely influenced children's reading skills but not math skills. Kindergarten also predicted faster reaction times on error trials, but did not predict electrophysiological correlates of motivation and EF. Both studies integrate brain and behavioral perspectives and methods in order to better understand the nature of EF and motivation in young children during the school transition period.

# Chapter I
## Introduction

Early school success is influenced by a variety of factors, particularly child-level cognitive processes such as motivation and executive functioning. Motivational beliefs and achievement-related emotions influence how children approach activities and goals and how they think about success and failure. Executive functioning (EF) is associated with successful behavioral regulation and early academic success. Being able to flexibly shift attention and strategies based on the situation, exercising self-control, remembering rules and directions in the face of distractions, and holding a belief that a goal is attainable rather than engaging in helpless cognitions, are aspects of EF and motivation that are crucial for academic success. However, even the strongest EF skills and adaptive patterns of motivation will occasionally fail, and individuals will make mistakes along the way. Exploring how children respond to their mistakes can yield insights into the nature of motivation and EF.

The dissertation highlights two original studies that integrate brain and behavioral perspectives and methods in order to better understand the nature of EF and motivation in young children during the school transition period. In particular, I investigate specific patterns of brain responses associated with error processing – namely, the error-related negativity (ERN) and error positivity (Pe) – using the event-related potential (ERP) technique. The ERN is thought to reflect processes associated with automatic error detection, while the Pe is thought to reflect the conscious awareness of and increased attention to the erroneous response, and may also reflect the emotional response to the mistake  (see Gehring, Liu, Orr, & Carp, 2012, for a review). Theoretical and empirical work has linked the ERN with processes underlying cognitive control and EF (e.g., Hirsh & Inzlicht, 2010; Lyons & Zelazo, 2011), while a growing number of investigations have explored the relation between motivation and the Pe (e.g., Moser, Schroder, Heeter, Moran, & Lee, 2011; Schroder, Moran, Donnellan, & Moser, 2014). While the nature of EF in young children is becoming increasingly clear, motivational processes in young children

have not received as much research attention. Moreover, given research demonstrating that motivation and EF skills are related to academic success (e.g., Berhenke, 2013; Blair & Razza, 2007; McClelland et al., 2007; Meece, Wigfield, & Eccles, 1990), a more nuanced understanding of these cognitive processes may facilitate the development of programs and strategies designed to promote these skills in young children.

In Chapter II, the links between children's motivational characteristics – in particular, perceived competence and intrinsic task value beliefs, two important aspects of expectancy-value theory (e.g., Wigfield & Eccles, 2000) – on the ERN and Pe are explored, as well as children's temperamental levels of anger/frustration, an important achievement-related emotion. The study finds that stronger perceived competence beliefs are related to a larger Pe, while stronger intrinsic task value beliefs are related to a smaller Pe. In addition, higher levels of temperamental anger/frustration are related to a larger Pe. These results suggest that individual differences in motivation in young children are related to electrophysiological processes associated with attention and emotion.

In Chapter III, contextual influences – specifically, school and classroom experiences – on motivation and EF are explored. Children's beliefs about learning and achievement are shaped by interactions with teachers and peers and their experiences in structured activities and assessment (e.g., Wigfield & Eccles, 2002), while programs designed to promote positive behavioral and social skills can facilitate the development of EF (e.g., Diamond, Barnett, Thomas, & Munro, 2007; Raver et al., 2011). Experiences in formal schooling environments may have a unique impact on brain and behavioral measures of children's EF and motivation. In this chapter, a regression discontinuity (RD) design is used to explore whether schooling has a unique effect on children's early reading and math outcomes, behavioral measures of inhibitory control, and electrophysiological measures related to EF and motivation. While a few empirical findings are highlighted, the primary focus of this chapter is to discuss how a RD design can be implemented in the context of a small-scale brain-behavior study. The chapter also includes a discussion on common issues and challenges that a researcher is likely to face when using RD, as well as recommendations on how to address these logistical and technical considerations.

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**Chapter II**

**Young children's motivational beliefs and achievement-related emotions are associated with electrophysiological measures of error monitoring processes**

**Abstract**

Motivational beliefs and emotions influence how children approach activities and goals, especially as they make mistakes during challenging tasks. Achievement goal theory and expectancy-value theory provide two theoretical perspectives through which motivation can be examined. The present study explores motivation in young children by studying the nature of their mistakes and their reactions to them, including the electrophysiology underlying error processing. Two event-related potential components, the error-related negativity (ERN) and error positivity (Pe), provide insights into the electrophysiological processes associated with mistakes. Behavioral and EEG data from 50 four- to six-year-old children revealed that motivational processes were not related to the ERN but rather to the Pe. Greater perceived competence beliefs were related to a larger Pe, while stronger intrinsic task value beliefs predicted a smaller Pe. Children's temperamental levels of anger/frustration − emotions associated with goal-directed and motivated behavior − were associated with a larger Pe. These findings provide support for the error awareness and affective response theories of the Pe, and suggest that individual differences in conscious error awareness, as indexed by the Pe, may reflect the nature of early motivational processes in young children.

## 1. Introduction

*1.1 Motivational processes*

Motivation is a set of beliefs, values, and emotions that influence how an individual tackles an activity or goal (Pintrich & Schunk, 2002). Motivation has been studied from different theoretical perspectives. Achievement goal theory focuses on the reasons for engaging in an activity. Individuals with learning or mastery orientations focus on increasing competence, whereas individuals with performance orientations focus on validating or confirming pre-existing

notions about ability (Dweck, 2003; Dweck, Mangels, & Good, 2004). Separately, expectancy-value theory focuses on how an individual's beliefs about her perceived competence and the degree to which she likes or values the activity influence achievement (Wigfield, Eccles, Schiefele, Roeser, & Davis-Kean, 2006). Other theories focus on the affective processes that accompany goal-directed behavior, such as anxiety and anger (Elliot & Thrash, 2002; Rothbart & Hwang, 2005).

In the face of difficulty, children can either be persistent and oriented towards mastering the activity, or can give up and exhibit feelings and behavior associated with helplessness (Smiley & Dweck, 1994). Understanding how individuals respond to mistakes as they work towards achieving a goal can help to reveal the nature of motivation in young children. For example, is a mistake a learning opportunity that can help a person to achieve higher outcomes in the future? Or is a mistake a cause for concern, prompting the person to question her ability and thereby altering her expectations? The aim of the present study is to explore the nature of children's mistakes and their responses to errors as a way to better understand early motivational processes.

*1.2 Motivation and children's mistakes*

Preschool-aged children exhibit mastery-oriented and helpless response patterns related to achievement goals (Smiley & Dweck, 1994; Ziegert, Kistner, Castro, & Robertson, 2001), and implicit theories of intelligence have been identified in children as young as five years of age (Bempechat, London, & Dweck, 1991). Within expectancy-value (E-V) theory, children possess beliefs about their abilities (or perceived competence) and what they value or enjoy (or subjective task value; Wigfield & Eccles, 2000). These beliefs, as well as emotional indicators of motivation, are related to early reading outcomes and school readiness indicators, respectively (Berhenke, 2013; Berhenke, Miller, Brown, Seifer, & Dickstein, 2011). The increased social comparison that children engage in, along with the greater focus on evaluation and comparison in academic contexts, shape growth of achievement motivation during the schooling years (Wigfield & Eccles, 2002). While we have learned a lot about motivation during the transition to middle school (e.g., Friedel, Cortina, Turner, & Midgley, 2010), we know relatively little about the nature of motivation during the transition to formal schooling, partly due to theoretical and methodological challenges associated with assessing motivation in this age group. Motivational

processes may be particularly activated during challenging situations in which making mistakes and experiencing temporary setbacks are not uncommon. How children react to these failure experiences may provide insights into the nature of their beliefs and values about achievement. In this study, we use the event-related potential (ERP) technique to explore specific patterns of brain responses associated with error processing as a way to better understand the nature of motivation in young children.

*1.3 Motivation and the error-related negativity (ERN)*

The error-related negativity (ERN) is seen as a negative-going deflection in an ERP waveform occurring about 50 milliseconds following an incorrect response on a speeded target discrimination task. The ERN is generated by the anterior cingulate cortex, a brain area implicated in cognitive control and executive functioning processes (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Coles, Meyer, & Donchin, 1990; Gehring, Goss, Coles, Meyer, & Donchin, 1993; see Gehring, Liu, Orr, & Carp, 2012, for a review). Theoretical accounts of the ERN include reinforcement learning (Holroyd & Coles, 2002) and conflict monitoring perspectives (Larson, Clayson, & Clawson, 2014; Yeung, Botvinick, & Cohen, 2004). Both models suggest that the ERN is related to error detection and that these detection processes are utilized to increase cognitive control (Hajcak, 2012). The ERN is present in children as young as three years of age with little evidence for age-related changes in ERN amplitude before age seven (Grammer, Carrasco, Gehring, & Morrison, 2014).

The ERN is sensitive to processes related to motivation. It is enhanced when subjects prioritize accuracy over speed when making responses (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990; Gehring et al., 1993), and is larger when monetary penalties for errors are increased compared to low-penalty trials (Hajcak, Moser, Yeung, & Simons, 2005). The ERN is related to intrinsic and extrinsic motivational orientations – conceptually related to achievement goal orientations – in third- to fifth-grade children (Fisher, Marshall, & Nanayakkara, 2009). The ERN is also thought to reflect the distress associated with the violation of expectancy caused by the error (Luu, Tucker, Derryberry, Reed, & Poulsen, 2003). The ERN may also be affected by the degree to which an individual cares about doing well on an activity (Segalowitz & Dywan, 2009). From an E-V perspective, expectancy can be understood as expectations or beliefs about

one's performance, and caring about doing well may reflect the degree to which an individual enjoys or likes the activity. Given these findings, we would expect that the E-V theory of motivation would be related to the ERN, such that strong expectancy and value beliefs would each be related to a larger ERN.

*1.4 Motivation and the error positivity (Pe)*

The Pe accompanies the ERN and is observed at centroparietal electrode sites, occurring about 200 to 500 ms after an incorrect response (Gehring et al., 2012). The error-awareness hypothesis suggests that the Pe reflects processes underlying the subject's conscious awareness and recognition of the error, whereas the affective processing hypothesis suggests that the Pe reflects the emotional response associated with the awareness of the mistake (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). Recent research has demonstrated a positive correlation between age and the magnitude of the Pe in young children, suggesting that the Pe may index aspects of development related to error processing such as processes underlying executive functions or other higher-order cognitive processes (Grammer et al., 2014).

If we understand motivation to be a set of beliefs, values, and emotions that influence engagement and achievement, these characteristics may be more closely related to cognitive processes associated with the awareness of one's responses as indexed by the Pe compared to processes underlying the ERN. Because the ERN is observed even when individuals are unaware that a mistake has been made (Endrass, Reuter, & Kathmann, 2007; Nieuwenhuis et al., 2001), the ERN may index an automatic process of error detection that is less sensitive to motivational processes compared to the Pe. Recent work provides support for this general hypothesis. Research on perfectionism suggests that higher levels of concern over mistakes are related to a larger Pe but not to the ERN (Tops, Koole, & Wijers, 2013). Research on ability mindsets, which are conceptually similar to achievement goals, has been particularly illuminating. Individuals with a growth mindset exhibit an enhanced Pe difference compared to individuals with a fixed mindset, with no associations with the ERN (Moser, Schroder, Heeter, Moran, & Lee, 2011). Recent findings from an experimental study in which growth and fixed mindsets were induced suggest that individual differences in ability mindsets are related to the magnitude of the P300

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and the late Pe, but not the ERN (Schroder, Moran, Donnellan, & Moser, 2014). Extending this logic to E-V theory, we might expect that individuals who believe they are good at an activity to be more conscious of their errors so that they can make appropriate adjustments in order to meet their expectations about their strong ability; this error awareness may be reflected in a larger Pe.

The Pe may also reflect the emotional response to making a mistake (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). Exploring achievement-related emotions can help us to better understand how emotions relate to motivational beliefs and values, as well as how these particular emotions might relate to the Pe. While previous research on error processing has focused on affective processes such as anxiety and fear (Brooker & Buss, 2014; Brooker, Buss, & Dennis, 2011; Hajcak & Foti, 2008; Meyer, Weinberg, Klein, & Hajcak, 2012), anger and frustration may provide additional insights into the nature of children's mistakes and their motivation. Anger and frustration may reflect approach motivational processes underlying goal-directed behavior and may reflect an adaptive motivational orientation associated with a drive and desire for achievement (Carver & Harmon-Jones, 2009; He et al., 2010; Lewis & Sullivan, 2005). In the present study, we explore whether individual differences in children's temperamental levels of anger and frustration are associated with variability in the Pe.

*1.5 Aims and hypotheses*

The study had three primary aims. First, we sought to better understand the nature of motivation in children aged four to six years. Second, we attempted to extend our recent findings by showing that the ERN and Pe can be reliably observed and measured in this age range in a different experimental setting. Third, we explored whether individual differences in young children's motivation were related to neural measures of error processing.

1. *Achievement goal theory:* Previous research has demonstrated that learning-oriented children engage in greater self-monitoring behaviors compared to performance-oriented children (Diener & Dweck, 1978), and that individuals with performance goals are less likely to attend to learning-relevant feedback compared to individuals with learning goals (Mangels, Butterfield, Lamb, Good, & Dweck, 2006). These group differences may extend to levels of attention devoted to a mistake. We predicted that learning-oriented

children would pay more attention to their mistakes in order to learn from them, and this attentional processing would be reflected in a larger Pe. On the other hand, because performance-oriented children are more interested in evaluations of their ability rather than engaging in the learning process, these children may devote less attention to their mistakes.

2. *Expectancy-value theory:* We predicted that children who express stronger beliefs about their high competence would pay more attention to their mistakes that are presumably unexpected given their stated beliefs, which would be reflected in a larger Pe. On the other hand, we predicted that children who express stronger intrinsic task value beliefs would pay less attention to their mistakes because engaging in the activity is intrinsically rewarding and performing well is not a major concern; these children should exhibit a smaller Pe. Given research suggesting that the ERN is related to the violation of expectancy caused by the error as well as the degree to which the individual cares about the activity, we expected children's expectancy and value beliefs to be related to a larger (i.e., more negative) ERN.

3. *Achievement-related emotions – Anger/frustration:* Because anger and frustration may be associated with goal-directed, motivated behavior and a drive for achievement, children with high temperamental levels of anger/frustration may exhibit a larger Pe. However, it is also possible that children who are temperamentally prone to anger and frustration may persist less and exhibit increased helpless behaviors in achievement situations. In this case, we may observe a smaller Pe associated with decrements in attention to their mistakes. Previous research also suggests that negative emotionality in young children is associated with reduced ERN amplitudes (Torpey et al., 2013); therefore, we expect anger/frustration to be related to a smaller (i.e., less negative) ERN in our sample.

## 2. Method

*2.1 Participants*

Sixty-five children (41 boys, 24 girls) between four and six years of age ($M = 5.30$ years, $SD = 0.86$) participated in this investigation. Participants were recruited through a variety of methods, including presentations at area preschools, posting of flyers in universities and childcare centers, and an online study recruitment database. The accompanying parent filled out a background

questionnaire. Reflecting the community from which the sample was recruited, the majority of children were Caucasian (80%); five children were African American, two children were Asian, and one child was American Indian/Alaska Native. Another five children were reported as being of mixed ethnicity, and one parent did not provide race/ethnicity information. Fifty-seven parents (88%) reported highest educational attainment of a college degree (or equivalent) or higher. Sixteen parents (25%) reported a total household income of less than $50,000. Parents reported on the child's health conditions; children were only included in the analysis if parents did not report any psychiatric, psychological, or neurological disorder.

Of the initial sample of 65 children who participated in the study, eight children did not participate in the EEG portion of the assessment due to refusal, lack of cooperation, or ineligibility based on parent report of the child's health condition. Of the 57 children with ERP data, five children were dropped from the analysis due to unusually poor data quality after visual inspection of the raw EEG data. Finally, of the 52 remaining children, two children committed fewer than six errors. Those two children were eliminated from the sample based on the criterion proposed by Pontifex and colleagues (Pontifex et al., 2010). Therefore, all analyses were conducted on a final sample of 50 children. This final sample included four children who did not contribute complete ERP data due to technical errors and child refusal to complete all eight blocks of the Go/No-Go task. Close inspection of the averaged waveforms for these children did not indicate any unusual distortions or artifacts in the correct and error waveforms. Averaging across different numbers of trials is generally permitted if linear mean amplitude measures are used (Luck, 2005).

*2.2 Procedure*
All testing took place in a child-friendly laboratory at the University of Michigan and was conducted by trained experimenters. Upon receiving verbal child assent, children completed a series of direct behavioral assessments designed to measure motivation, metacognitive knowledge, executive functioning, and early academic skills. Children were given stickers at regular intervals to promote enthusiasm and engagement in the tasks, and were also given opportunities to take breaks in the adjoining waiting room/play area. In the adjoining room, the accompanying parent filled out a background questionnaire. The door to the testing room was

kept open in order for the parent to be able to quietly supervise what was going on during testing. After the behavioral assessments, children participated in ERP testing.

*2.3 Motivation assessments*

*2.3.1 Achievement goals*

Children played a game called the Wedgits puzzle – a type of challenge puzzle task commonly used in studies of motivation in young children (e.g., Smiley & Dweck, 1994; Ziegert et al., 2001) – which assessed children's achievement goal orientations. This puzzle involves colored blocks of various shapes and sizes, and was selected to be similar to toys and games that children might be familiar with at their preschools and homes. Children were shown a card with a design and asked to arrange the blocks to match the design on the card. If the child successfully completed the first design in four minutes or less, a second, more challenging design was provided. If needed, children received assistance on the first design but not for subsequent designs. The task continued until the child attempted a design that she was unable to successfully complete in four minutes. After the child failed to complete a puzzle, the child was asked: "If you had more time to work, would you like to keep trying [the easier, completed puzzle] or build [the harder, incomplete puzzle] again?" Choosing the easier puzzle is indicative of a focus on performance (performance goal) rather than a focus on mastering a challenging task (learning or mastery goal). This classification system has been used in motivation studies with young children (Smiley & Dweck, 1994; Ziegert et al., 2001). The protocol for the achievement goal measure is presented in **Appendix 1**.

*2.3.2 Expectancy-value theory*

The *puppet interview* is an eight-item measure adapted from the Puppet Interview Scales of Competence in and Enjoyment of Science (PISCES; Mantzicopoulos, Patrick, & Samarapungavan, 2008) that assesses a child's competence and value beliefs about the Wedgits puzzle task that was just completed. Children were presented with a group of five puppets of individual children from diverse backgrounds, and were asked to choose the one that was most like them. Once the puppet was chosen, a corresponding puppet was presented that looked identical to the chosen puppet except for a superficial feature (such as a different hairstyle or outfit) in order to differentiate between puppets. Then, the puppets "spoke" to the child, with one

puppet saying "I like doing puzzles like this one" and the other saying "I don't like puzzles like this one." Then, the experimenter asked the child to point to the puppet that thought like her. Children responded to four dichotomous statements that capture intrinsic task value beliefs (e.g., I have/don't have fun doing puzzles) and four dichotomous statements that capture perceived competence (e.g., I know/don't know how to do puzzles). Scores for each subscale could range from zero to four – for example, a score of three on the perceived competence subscale would denote that the child selected three positively-valenced statements (or conversely, one negatively-valenced statement was selected). The puppet interview protocol is presented in **Appendix 2**.

### 2.3.3 Anger/frustration

Parents completed a background questionnaire that included the short form of the Children's Behavior Questionnaire (Putnam & Rothbart, 2006). This 94-item measure assesses various aspects of temperament in children aged three through eight years. We chose to focus specifically on the anger/frustration subscale given its close theoretical relation to motivational processes; the subscale is defined as the "amount of negative affect related to interruption of ongoing tasks or goal blocking" (Rothbart, Ahadi, Hershey, & Fisher, 2001). Questions in this subscale include: "Gets quite frustrated when prevented from doing something s/he wants to do" and "Gets angry when called in from play before s/he is ready to quit." These questions may reflect a child's affective disposition related specifically to motivational processes during goal-directed activity. Each question was answered on a seven-point Likert-type scale, ranging from one ("Extremely untrue of your child") to seven ("Extremely true of your child"). The full list of questions in the subscale is presented in **Appendix 3**.

### 2.4 Go/No-Go task

Participants played a child-friendly Go/No-Go task called the Zoo Game (Grammer et al., 2014; Lamm et al., 2014; McDermott, White, Degnan, Henderson, & Fox, 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 **Figure 1**.
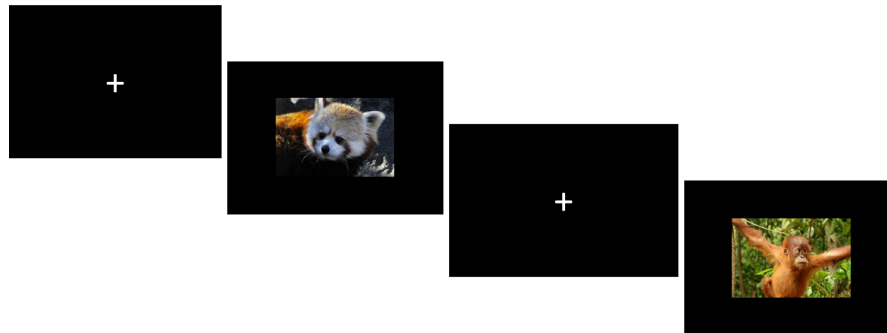


**Figure 1:** Sample images from the Go/No-Go Zoo Game

The Zoo Game was presented using EPrime 2.0 (Psychology Software Tools, 2010) on a 22-inch 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 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 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, they could get free and help catch the other animals again. To sustain enthusiasm and task engagement, children were provided with short breaks as necessary.

*2.5 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 vertical and horizontal eye movement artifacts. Electrode offsets were between ± 30 μv. 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 μV, (2) a change greater than 50 μV was measured between two consecutive data points, and (3) the data deviated by more than +25 or -100 dB in a frequency window of 20-40 Hz in order to detect and remove muscle artifacts. From the continuous EEG, 1,000 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, Coles, & Donchin (1983). ERP averages were baseline corrected by subtracting from each data point the average activity in a 300 to 200 ms window prior to the response. Each trial was then visually examined for artifacts and rejected if muscle or other artifacts were still present after the 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 -50 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., Fz, FCz, Cz, CPz, Pz). Statistical analyses were conducted using Stata 13.1.

## 3. Results

*3.1 Attrition analysis*

Looking at our key behavioral measures, independent group t-tests showed that there were no differences between children who were included in the analysis and children who were excluded on age, sex, parent employment status, response accuracy during the Zoo Game, reaction time on correct trials, and reaction time on error trials. However, children with parents who did not have a graduate or professional degree were more likely to be excluded from the analysis, $t(63) = -2.33$, $p = .02$), as well as children living in households with incomes of less than \$50,000, $t(63) = 2.32$, $p = .02$).

*3.2 Motivation*

*3.2.1 Achievement goals*

Thirty-seven children exhibited performance goals on the Wedgits puzzle. That is, 74% of children would have chosen to work on the easier puzzle if they had more time. This contrasts with previous research suggesting that young children seem to be evenly split between performance goals and learning goals (Smiley & Dweck, 1994; Ziegert et al., 2001).

*3.2.2 Expectancy-value theory*

Consistent with previous research showing that young children are optimistic about their abilities (Eccles, Wigfield, Harold, & Blumenfeld, 1993; Nicholls, 1979; Stipek & Greene, 2001), we found that children's beliefs about their perceived competence on the puzzle task and their beliefs about liking and enjoying the puzzle activity were high. 43 children (86 percent) scored three or four out of four positive statements for perceived competence, and 47 children (94 percent) scored three or four out of four positive statements for intrinsic task value.

*3.2.3 Anger/frustration*

The anger/frustration subscale of the CBQ exhibited sufficient scale reliability (6 items, $\alpha = .78$), suggesting that the questions accurately reflected the same underlying construct. On average, parents rated their children as being moderate on temperamental anger/frustration ($M = 4.11$, *SD* $= 1.18$, Range $= 1.33$-$6.33$).

## 3.3 Relating measures of motivation

Because of the non-normal nature of the motivation variables drawn from direct child assessments, the Wilcoxon rank-sum (Mann-Whitney) test and Spearman correlations were used. Children who exhibited a learning goal had stronger beliefs about their perceived competence on the puzzle task compared to children who exhibited a performance goal, $z$ = -2.36, $p$ = .02; a follow-up non-parametric equality-of-medians test confirms this finding, $X^2(1)$ = 6.76, $p < .01$. There was no significant correlation between children's perceived competence beliefs and their intrinsic task value beliefs, $r_s$ = .10, $p$ = .48, consistent with research suggesting that these beliefs are distinct from each other, particularly in younger children (Wigfield & Eccles, 2000; Wigfield et al., 1997). Motivational characteristics were not associated with age.

## 3.4 ERP behavioral measures

Children's accuracy and reaction time on correct and error trials are presented in **Table 1**. Errors were defined as the number of errors of commission during No-Go trials, excluding errors of omission during Go trials. Consistent with previous research, children were slower in responding on correct trials compared to error trials; this difference was statistically significant, $t(1,49)$ = 13.60, $p < .001$. Children who had higher temperamental levels of anger/frustration had a marginally higher error rate on the Zoo Game, $r$ = .24, $p$ = .06; no other motivation variables were related to the ERP behavioral measures. Although a post-error slowing phenomenon was observed in our sample, none of the motivation variables was related to the reaction time on trials immediately following an error.

**Table 1:** Behavioral performance on the Zoo Game

| Variable | Mean | SD | Range |
|---|---|---|---|
| Number of correct trials | 203.60 | 34.90 | 72 – 239 |
| Number of error trials | 28.38 | 12.49 | 6 – 58 |
| Percent correct (Go trials) | 87.12 | 10.31 | 64.58 – 99.58 |
| Percent incorrect (No-Go trials) | 36.40 | 15.64 | 3.17 – 72.50 |
| Reaction time (correct trials) | 611.84 | 75.52 | 482.06 – 817.10 |
| Reaction time (error trials) | 497.68 | 63.68 | 360.94 – 613.95 |

## 3.5 ERP measures

### 3.5.1 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 2**, the ERN was maximal at Fz and the Pe on error trials was maximal at CPz. Difference scores were also calculated in order to properly account for brain activity occurring during both correct and incorrect responses. The ΔERN 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 -50 to 50 ms window, and the ΔPe was defined as the brain activity on error trials minus the brain activity on correct trials in a 200 to 500 ms window. The ΔERN was maximal at FCz and ΔPe was maximal at Pz.

**Table 2:** Mean amplitudes for ERP components at midline electrode sites

| Component | Fz | FCz | Cz | CPz | Pz |
|---|---|---|---|---|---|
| ERN | -6.59 | -6.17 | -1.94 | 3.08 | 6.60 |
| CRN | -2.13 | -1.01 | 2.52 | 4.52 | 3.64 |
| ΔERN | -4.46 | -5.16 | -4.47 | -1.44 | 2.97 |
| Pe (error trials) | -0.40 | 4.58 | 9.31 | 14.31 | 13.01 |
| Pe (correct trials) | 7.34 | 6.75 | 5.03 | 3.56 | -2.34 |
| ΔPe | -7.74 | -2.17 | 4.28 | 10.76 | 15.35 |

### 3.5.2 ERN and CRN

Waveforms for response-locked ERPs for error and correct trials are shown in **Figure 2** at midline electrode sites. The ERN was observed as a negative deflection peaking in a window between 50 ms before the response and 50 ms after the response at frontocentral electrode sites. Given previous research demonstrating that the ERN is largest at frontocentral electrode sites, we focused our analysis of variance (ANOVA) at these sites. A 2 (Electrode Site: Fz, FCz) x 2 (Trial Type: Correct, Error) repeated measures ANOVA confirmed that there was a marginally significant main effect of electrode site, $F(1,49) = 2.75$, $p = .10$, as well as a significant main effect of trial type, $F(1,49) = 107.18$, $p < .001$. The non-significant interaction between electrode site and trial type suggests that the amplitude difference between correct and error trials did not vary as a function of electrode site, $F(1,49) = 0.57$, $p = .45$. Follow up post-hoc paired sample t-

tests demonstrated that the ERN was more negative at Fz compared to Cz, $t(49) = -5.87$, $p < .001$ and Pz, $t(49) = -11.11$, $p < .001$, but that the ERN at Fz was not significantly different from the ERN at FCz, $t(49) = -.78$, $p = .44$. When exploring mean differences between the ERN and the CRN, the $\Delta$ERN at Fz was not significantly different from the $\Delta$ERN at FCz, $t(49) = 1.49$, $p = .14$ and at Cz, $t(49) = .01$, $p = .99$, but was significantly different at CPz, $t(49) = -2.86$, $p < .01$ and Pz, $t(49) = -5.91$, $p < .001$.

### 3.5.3 Pe

The Pe was observed as a slow positive deflection between 200 and 500 ms after the response at centroparietal electrode sites. Given previous research demonstrating that the Pe is largest at centroparietal electrode sites, we focused our ANOVA at these sites. A 2 (Electrode Type: CPz, Pz) x 2 (Trial Type: Correct, Error) repeated measures ANOVA confirmed that there was a significant main effect of electrode site, $F(1,49) = 23.98$, $p < .001$, as well as a significant main effect of trial type, $F(1,49) = 314.80$, $p < .001$. 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, $F(1,49) = 9.73$, $p < .01$. Follow up post-hoc paired sample t-tests showed that the Pe was more positive on error trials at Pz compared to Cz, $t(49) = 3.03$, $p < .01$ and Fz, $t(49) = 8.95$, $p < .001$ but that the Pe on error trials at Pz was only marginally different from the Pe on error trials at CPz, $t(49) = -1.90$, $p = .06$. When exploring mean differences between the Pe on error trials and the Pe on correct trials, the $\Delta$Pe at Pz was significantly different from the $\Delta$Pe at CPz, $t(49) = 6.41$, $p < .001$, Cz, $t(49) = 8.29$, $p < .001$, FCz, $t(49) = 9.68$, $p < .001$, and Fz, $t(49) = 13.16$, $p < .001$.
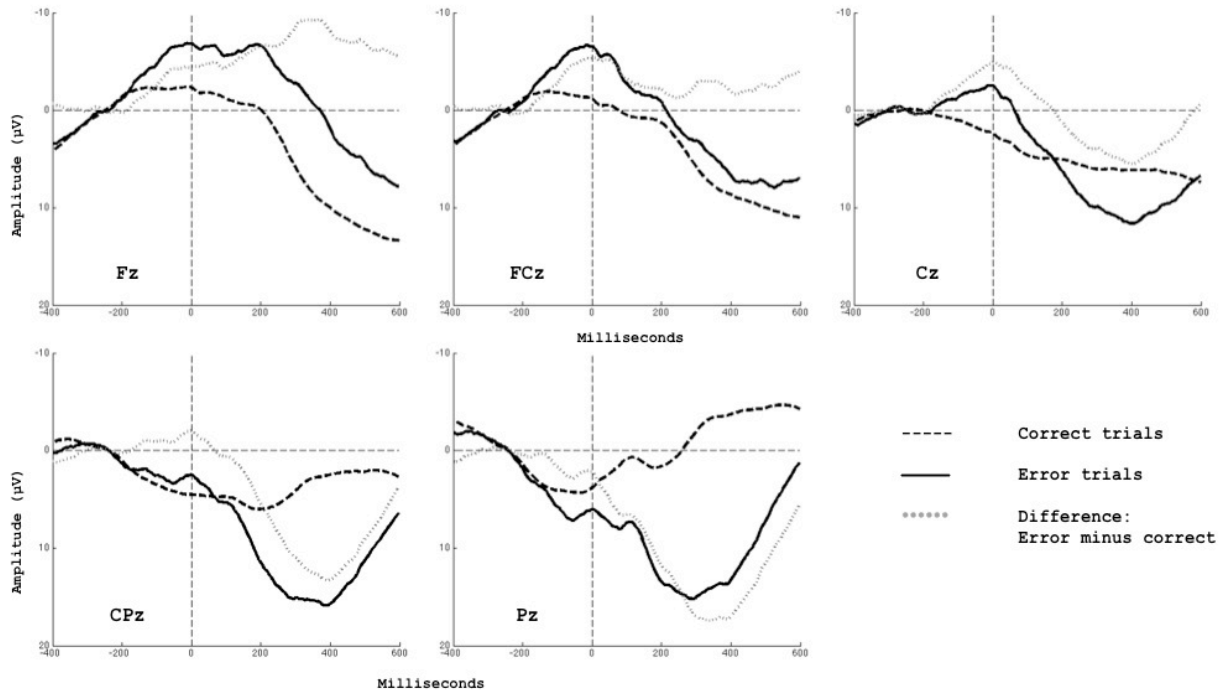
**Figure 2:** Grand average waveforms at midline electrode sites. The vertical dashed line at time zero indicates the time of the response (button-press switch closure).

### 3.6 Associations between motivation and ERPs

### 3.6.1 Joint generalized least squares framework: Seemingly unrelated regression

In ERP research, we are often interested in determining not only whether variables are significant predictors of the magnitude of an ERP component at an electrode site, but also whether the effects at adjacent electrode sites are significantly different from each other. In order to explore the relation between each of our four motivation variables to the magnitude of the ERN and Pe, we conducted a seemingly unrelated regression (SUR). A SUR allows us to test not only whether the predictors are significantly different from zero, but also whether the predictors between the equations are significantly different *from each other*. A SUR, which generates joint generalized least squares (JGLS) estimates, allows us to test multiple equations with different dependent variables (e.g., Pe at CPz and Pe at Pz) by taking into account the shared covariance between the error terms in each equation in order to improve the efficiency of the regression estimates and standard errors (Zellner, 1962). We can also use SUR to explore the effects of the motivation variables on the difference scores, ΔERN and ΔPe, thereby exploring whether the effects of the motivation variables are sensitive to the type of measurement. We would expect to

observe greater stability in the difference measures, as these measures account for the brain activity that is occurring during both correct and incorrect trials.

### 3.6.2 Associations between motivation and the ERN

For each motivation variable, we estimated the following SURs:

$$y_1 = \alpha_0 + \alpha_1 mot + \varepsilon$$
$$y_2 = \beta_0 + \beta_1 mot + e$$

and

$$y_{1d} = \alpha_{0d} + \alpha_{1d} mot + \varepsilon_d$$
$$y_{2d} = \beta_{0d} + \beta_{1d} mot + e_d$$

where $y_1$ denotes the magnitude of the ERN at Fz, $y_2$ denotes the magnitude of the ERN at FCz, $y_{1d}$ denotes the magnitude of the $\Delta$ERN at Fz, $y_{2d}$ denotes the magnitude of the $\Delta$ERN at Pz, mot represents the motivation variable, and $\varepsilon/e$ and $\varepsilon_d/e_d$ are the error terms. All reported regression estimates are drawn from 50 observations.

### 3.6.2.1 Achievement goal orientation and the ERN

The JGLS estimates are presented in **Table 3.1**. There was not an effect of achievement goal orientation on the ERN at Fz, but there was a marginally significant effect at FCz such that a learning goal orientation was associated with a smaller (or less negative) ERN. When using the difference scores as dependent variables, there was no effect of achievement goal orientation on the $\Delta$ERN at either electrode site. When testing the null hypothesis that $\alpha_1 = \beta_1$ – that is, that the effect of achievement goal orientation on the ERN at Fz is not significantly different from the effect at FCz – we found that the coefficients were marginally different from each other, $X^2(1) = 3.10$, $p = .08$. Likewise, when testing whether $\alpha_{1d} = \beta_{1d}$, we found that the coefficients were significantly different from each other, $X^2(1) = 3.04$, $p = .08$.

**Table 3.1:** JGLS estimates for achievement goal orientation on the ERN and $\Delta$ERN

| VARIABLES | (1a) ERN (Fz) | (1b) ERN (FCz) | (2a) $\Delta$ERN (Fz) | (2b) $\Delta$ERN (FCz) |
|---|---|---|---|---|
| Achievement goal orientation | 0.171 (1.554) | 2.235+ (1.328) | -1.163 (1.635) | 0.629 (1.631) |
| R-squared | 0.000 | 0.054 | 0.010 | 0.003 |

Note: Standard errors in parentheses; + p<0.10

Despite the marginally significant effect of achievement goal orientation on the ERN at FCz, it is difficult to interpret this result in the context of the other null findings. We would expect the difference score measure of the ERN to be a more reliable measure, as it accounts for the brain activity occurring on correct trials. However, achievement goal orientation did not have an effect on the ΔERN at either electrode site. Moreover, the effects of achievement goal orientation were different across electrode sites, as evidenced by the marginally significant chi-square tests. Given the lack of consistent findings across the two adjacent electrode sites and across type of measurement, our achievement goal orientation variable may not be accurately capturing the underlying construct that it is intended to measure.

*3.6.2.2 Perceived competence beliefs and the ERN*

The JGLS estimates are presented in **Table 3.2**. We found that perceived competence beliefs did not have a significant effect on the magnitude of the ERN, regardless of measurement type or electrode site.

**Table 3.2:** JGLS estimates for perceived competence beliefs on the ERN and ΔERN

| VARIABLES | (1a) ERN (Fz) | (1b) ERN (FCz) | (2a) ΔERN (Fz) | (2b) ΔERN (FCz) |
|---|---|---|---|---|
| Perceived competence beliefs | 0.885 (0.958) | 0.626 (0.844) | 1.250 (1.006) | 1.007 (1.006) |
| R-squared | 0.017 | 0.011 | 0.030 | 0.020 |

Note: Standard errors in parentheses

*3.6.2.3 Intrinsic task value beliefs and the ERN*

The JGLS estimates are presented in **Table 3.3**. We found that intrinsic task value beliefs did not have a significant effect on the magnitude of the ERN, regardless of measurement type or electrode site.

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**Table 3.3:** JGLS estimates for intrinsic task value beliefs on the ERN and ΔERN

| VARIABLES | (1a) ERN (Fz) | (1b) ERN (FCz) | (2a) ΔERN (Fz) | (2b) ΔERN (FCz) |
|---|---|---|---|---|
| Intrinsic task value beliefs | -0.551 (1.124) | -1.066 (0.978) | -0.032 (1.191) | -0.098 (1.184) |
| R-squared | 0.005 | 0.023 | 0.000 | 0.000 |

Note: Standard errors in parentheses

### 3.6.2.4 Anger/frustration and the ERN

The JGLS estimates are presented in **Table 3.4**. We found that there was a significant negative effect of anger/frustration on the magnitude of the ERN at Fz. That is, children who had higher temperamental levels of anger/frustration exhibited a more negative ERN. However, this effect was not present at FCz. This contrasts with our achievement goal orientation findings in which we found a marginal effect at FCz but not at Fz. When testing the null hypothesis that $\alpha_1 = \beta_1$, we found that the coefficients were not different from each other, $X^2(1) = 2.12$, $p = .15$. This chi-square test suggests that the effect of anger/frustration on the ERN is significantly different from zero at Fz, and the magnitude of this effect is not statistically different from the effect at FCz. We did not find any significant effects when using the difference score measure of the ERN at either electrode site.

**Table 3.4:** JGLS estimates for anger/frustration on the ERN and ΔERN

| VARIABLES | (1a) ERN (Fz) | (1b) ERN (FCz) | (2a) ΔERN (Fz) | (2b) ΔERN (FCz) |
|---|---|---|---|---|
| Anger / frustration | -1.105* (0.560) | -0.462 (0.506) | -0.625 (0.608) | -0.427 (0.608) |
| R-squared | 0.072 | 0.016 | 0.021 | 0.010 |

Note: Standard errors in parentheses; * p<0.05

### 3.6.2.5 Interim summary of individual SURs on the ERN

The results presented above provide little evidence that achievement goal orientation, perceived competence beliefs, intrinsic task value beliefs, and temperamental anger/frustration are related in a consistent way to the magnitude of the ERN. However, we find a much more interesting pattern of results when looking at the error positivity.

## 3.6.3 Associations between motivation and the Pe

For each motivation variable, we estimated the following SURs:

$$y_1 = \alpha_0 + \alpha_1 \text{mot} + \varepsilon$$
$$y_2 = \beta_0 + \beta_1 \text{mot} + e$$

and

$$y_{1d} = \alpha_{0d} + \alpha_{1d}\text{mot} + \varepsilon_d$$
$$y_{2d} = \beta_{0d} + \beta_{1d}\text{mot} + e_d$$

where $y_1$ denotes the magnitude of the Pe at CPz, $y_2$ denotes the magnitude of the Pe at Pz, $y_{1d}$ denotes the magnitude of the $\Delta$Pe at CPz, $y_{2d}$ denotes the magnitude of the $\Delta$Pe at Pz, mot represents the motivation variable, and $\varepsilon/e$ and $\varepsilon_d/e_d$ are the error terms. As before, all reported regression estimates are drawn from 50 observations.

## 3.6.3.1 Achievement goal orientation and the Pe

The JGLS estimates are presented in **Table 3.5**. There was a significant effect of achievement goal orientation on the magnitude of the Pe on error trials at CPz such that a learning goal orientation is related to a larger Pe, but there was no such effect at Pz. Moreover, when using the difference scores as dependent variables, there was no effect of achievement goal orientation on the $\Delta$Pe at either electrode site. When testing the null hypothesis that $\alpha_1 = \beta_1$, we found that the coefficients were significantly different from each other, $X^2(1) = 7.61$, $p < .01$. This pattern of inconsistent results is very similar to what we found for the ERN, providing additional evidence that our achievement goal orientation variable may lack sufficient internal validity that would allow us to draw definitive conclusions about the relation between achievement goal orientation and error processing.

**Table 3.5:** JGLS estimates for achievement goal orientation on the Pe and $\Delta$Pe

| VARIABLES | (1a) Pe (CPz) | (1b) Pe (Pz) | (2a) $\Delta$Pe (CPz) | (2b) $\Delta$Pe (Pz) |
|---|---|---|---|---|
| Achievement goal orientation | 5.194* (2.215) | 1.211 (1.906) | 3.397 (2.599) | 0.053 (2.679) |
| R-squared | 0.099 | 0.008 | 0.033 | 0.000 |

Note: Standard errors in parentheses; * p<0.05

## 3.6.3.2 Perceived competence beliefs and the Pe

The JGLS estimates for perceived competence beliefs are presented in **Table 3.6.** These results indicate that higher perceived competence beliefs are related to a larger Pe. There was a significant effect of perceived competence beliefs on the magnitude of the Pe on error trials at both CPz and Pz, although the effect at CPz is marginal. Although there was a non-significant finding for ΔPe at CPz, these beliefs were significant for ΔPe at Pz. When testing the null hypothesis that $\alpha_1 = \beta_1$, we found that the coefficients were not significantly different from each other, $X^2(1) = .59$, $p = .44$. Likewise, when testing whether $\alpha_{1d} = \beta_{1d}$, we found that the coefficients were not significantly different from each other, $X^2(1) = 2.06$, $p = .15$. That is, the effect of perceived competence beliefs on the magnitude of the ΔPe at Pz was significantly different from zero, and importantly, this effect was not statistically different from the effect at CPz. This helps us to place the non-significant finding at CPz in a more appropriate context, which would not be feasible in a traditional ordinary least squares regression framework because in that framework we cannot test coefficients across regressions. **Figure 3** presents a scatterplot of the bivariate association between children's perceived competence beliefs and the ΔPe at Pz.

**Table 3.6:** JGLS estimates for perceived competence beliefs on the Pe and ΔPe

| VARIABLES | (1a) Pe (CPz) | (1b) Pe (Pz) | (2a) ΔPe (CPz) | (2b) ΔPe (Pz) |
|---|---|---|---|---|
| Perceived competence beliefs | 2.375+ (1.411) | 3.108** (1.106) | 2.049 (1.618) | 3.463* (1.592) |
| R-squared | 0.054 | 0.136 | 0.031 | 0.086 |

Note: Standard errors in parentheses; ** p<0.01, * p<0.05, + p<0.10
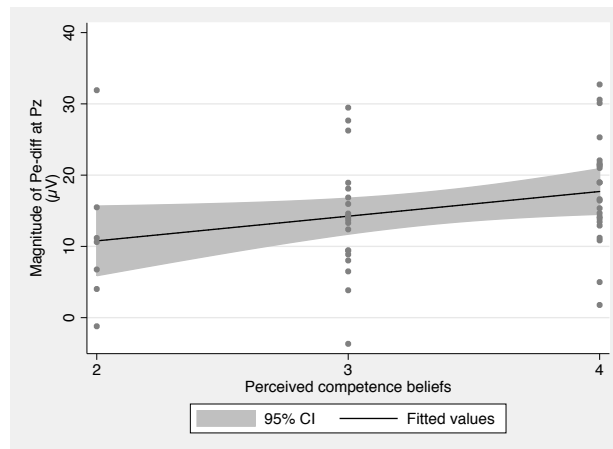


**Figure 3:** Bivariate scatterplot of ΔPe at Pz and perceived competence beliefs

*3.6.3.3 Intrinsic task value beliefs and the Pe*

The JGLS estimates for intrinsic task value beliefs are presented in **Table 3.7.** In contrast to perceived competence beliefs, higher intrinsic task value beliefs were related to a smaller Pe. There was a significant effect of intrinsic beliefs on the magnitude of the Pe on error trials at CPz, while the effect at Pz approached trend significance. There was also a significant effect for $\Delta$Pe at both CPz and Pz. When testing the null hypothesis that $\alpha_1 = \beta_1$, we found that the coefficients were significantly different from each other, $X^2(1) = 9.96$, $p < .01$. However, when testing whether $\alpha_{1d} = \beta_{1d}$, we found that the coefficients were not significantly different from each other, $X^2(1) = 1.45$, $p = .23$. **Figure 4** presents a scatterplot of the bivariate association between children's intrinsic task value beliefs and the $\Delta$Pe at Pz.

**Table 3.7:** JGLS estimates for intrinsic task value beliefs on the Pe and $\Delta$Pe

| VARIABLES | (1a) Pe (CPz) | (1b) Pe (Pz) | (2a) $\Delta$Pe (CPz) | (2b) $\Delta$Pe (Pz) |
|---|---|---|---|---|
| Intrinsic task value beliefs | -5.290*** (1.516) | -2.053 (1.356) | -5.741** (1.735) | -4.349* (1.841) |
| R-squared | 0.196 | 0.044 | 0.180 | 0.100 |

Note: Standard errors in parentheses; *** p<0.001, ** p<0.01, * p<0.05
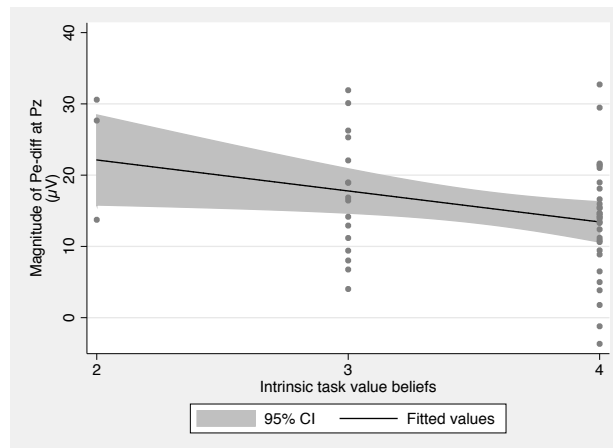


**Figure 4:** Bivariate scatterplot of $\Delta$Pe at Pz and intrinsic task value beliefs

*3.6.3.4 Anger/frustration and the Pe*

The JGLS estimates for anger/frustration are presented in **Table 3.8.** These results indicate that higher levels of anger/frustration were related to a larger Pe. The effect of anger/frustration on the Pe on error trials at CPz approached trend significance, but there was not a significant effect at Pz. There was a significant effect for $\Delta$Pe at both CPz and Pz, though the effect at CPz is marginal. When testing the null hypothesis that $\alpha_1 = \beta_1$, we found that the coefficients were not significantly different from each other, $X^2(1) = .40$, $p = .53$. Likewise, when testing whether $\alpha_{1d} = \beta_{1d}$, we found that the coefficients were not significantly different from each other, $X^2(1) = .14$, $p = .71$. **Figure 5** presents a scatterplot of the bivariate association between children's anger/frustration and the $\Delta$Pe at Pz.

**Table 3.8:** JGLS estimates for anger/frustration on the Pe and $\Delta$Pe

| VARIABLES | (1a) Pe (CPz) | (1b) Pe (Pz) | (2a) $\Delta$Pe (CPz) | (2b) $\Delta$Pe (Pz) |
|---|---|---|---|---|
| Anger / frustration | 1.338 (0.852) | 0.974 (0.702) | 1.797+ (0.955) | 2.025* (0.960) |
| R-squared | 0.047 | 0.037 | 0.066 | 0.082 |

Note: Standard errors in parentheses; * p<0.05, + p<0.10
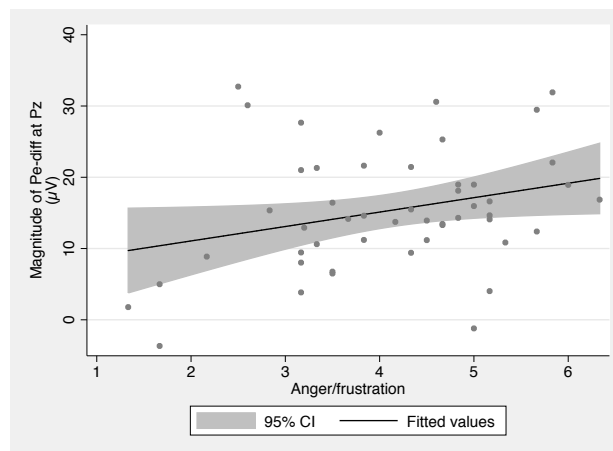


**Figure 5:** Bivariate scatterplot of $\Delta$Pe at Pz and anger/frustration

*3.6.3.5 Interim summary of individual SURs on the Pe*

The results of the individual seemingly unrelated regressions suggest that there are consistent and reliable effects of perceived competence beliefs, intrinsic task value beliefs, and anger/frustration on the magnitude of the Pe across midline centroparietal electrode sites. This

becomes particularly clear when we focus on the ΔPe. As previously noted, we expected the difference measures to have greater stability and predictive power, as these measures account for the brain activity that is occurring during both correct and incorrect trials. For each of these three motivation variables, there was at least one significant effect at CPz and Pz on the ΔPe, and importantly, we failed to reject the null hypothesis that $\alpha_{1d} = \beta_{1d}$. This indicates that there was a valid and stable relation between these motivation variables and the ΔPe across adjacent midline electrode sites. Waveforms comparing high and low groups on each of the three motivation variables are presented below in **Figures 6, 7, and 8.**
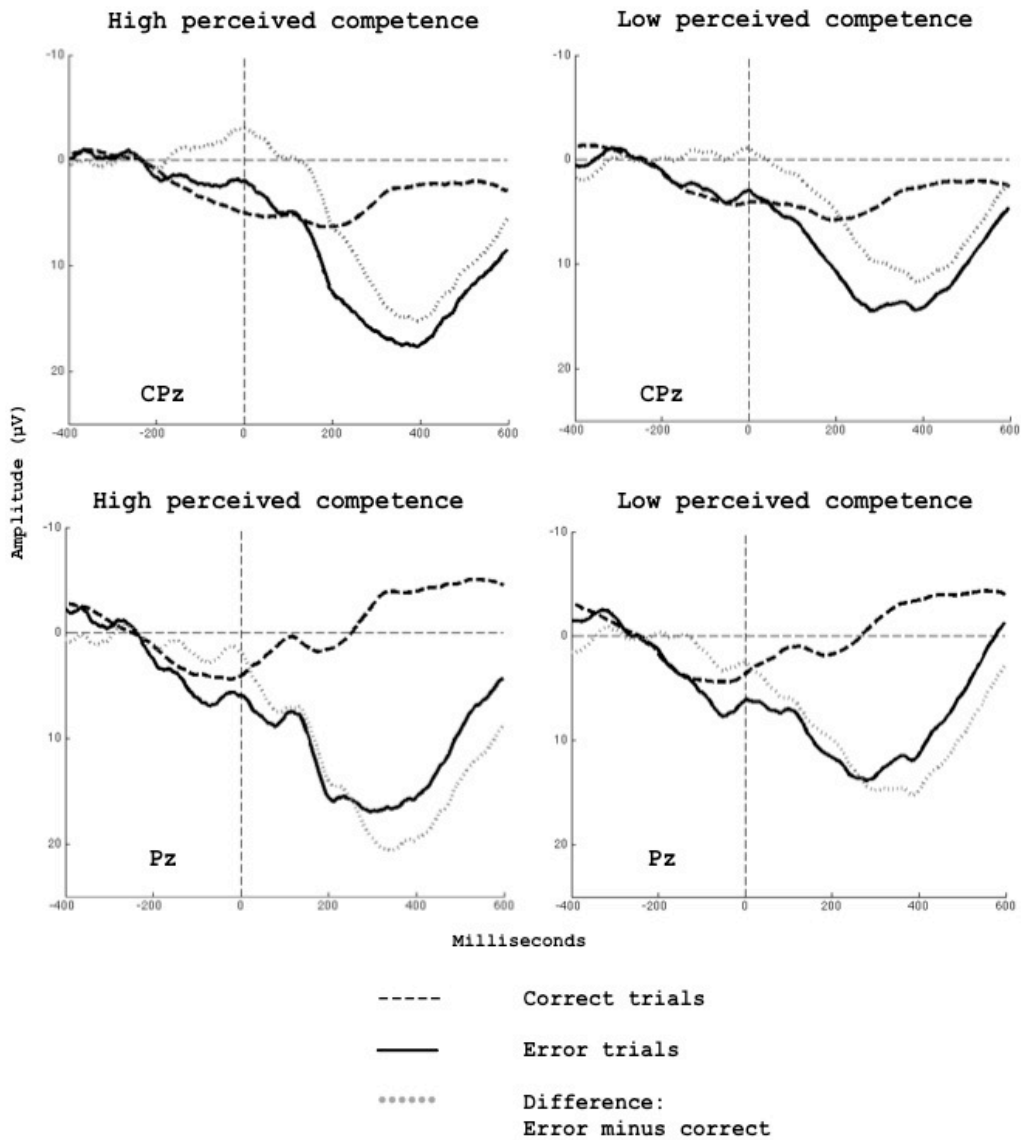


**Figure 6:** Waveforms for children with high perceived competence beliefs and low perceived competence beliefs at electrode sites CPz and Pz
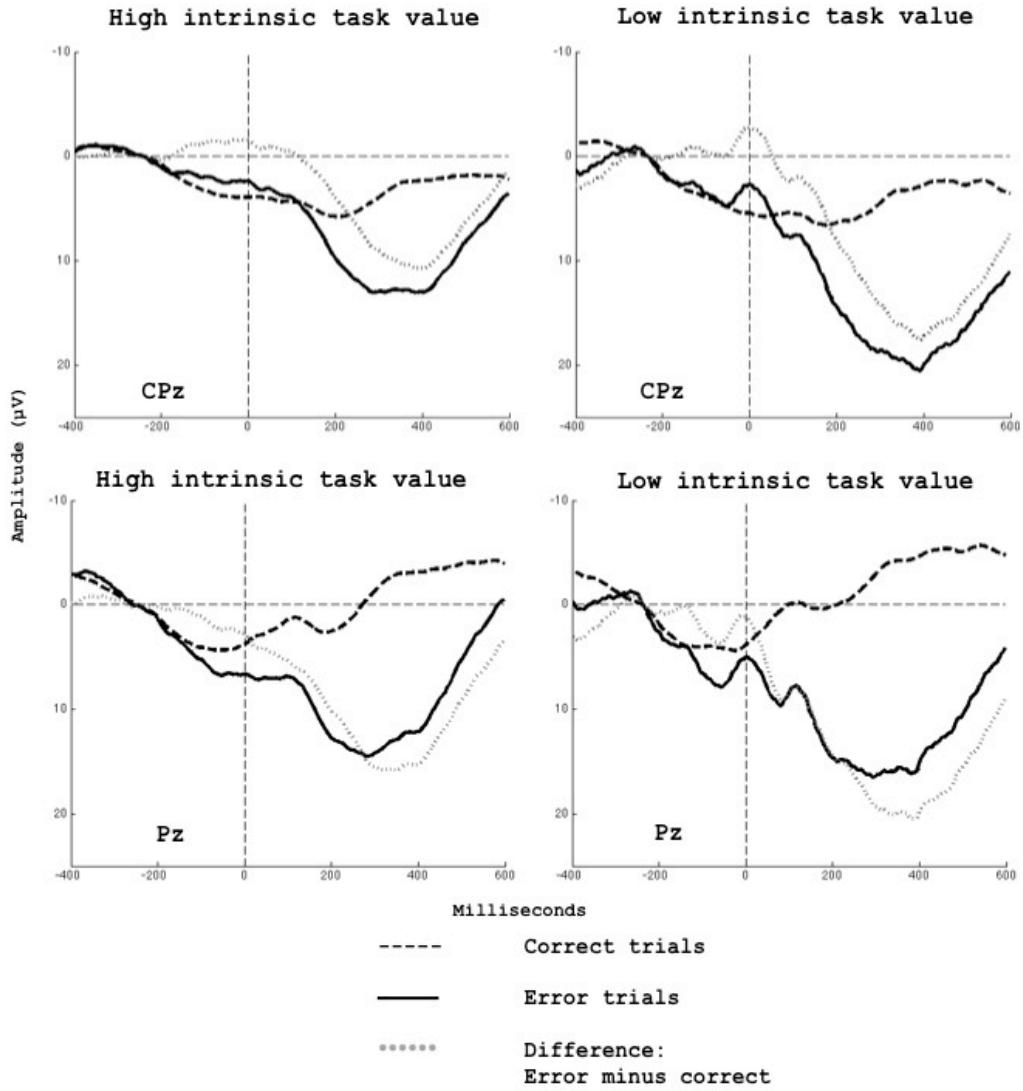
**Figure 7:** Waveforms for children with high intrinsic task value beliefs and low intrinsic task value beliefs at electrode sites CPz and Pz
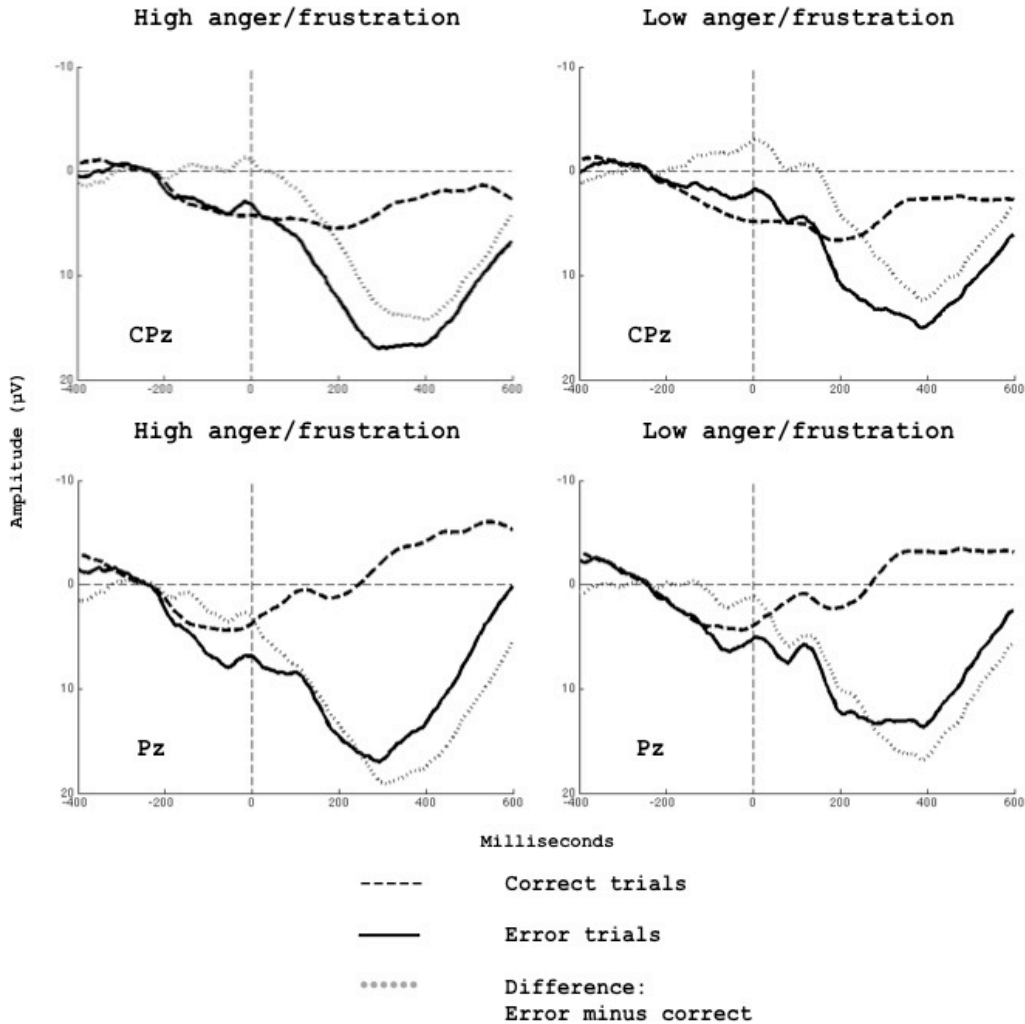
**Figure 8:** Waveforms for children with high anger/frustration and low anger/frustration at electrode sites CPz and Pz

However, for the achievement goal orientation variable, the only significant effect was found at CPz for the Pe on error trials. Even though this effect was significantly different from zero, we found that this effect was significantly different from the effect at Pz, suggesting that the effect of achievement goal orientation – unlike the other motivation variables – depends on where the effect is measured. Because achievement goal orientation fails to capture a stable relation across CPz and Pz regardless of the type of Pe measure used, it would be difficult to interpret findings for this variable. Therefore, we dropped the achievement goal orientation variable and focused on the difference score measure of the Pe in subsequent analyses.

*3.6.4 Multiple regression of motivation variables on the Pe*

We jointly explored the three motivation variables that exhibited a stable pattern of relations in order to assess the predictive power of each variable while holding the other variables constant.

We estimated the following SUR:

$$y_{1d} = \alpha_{0d} + \alpha_{1d}pc + \alpha_{2d}itv + \alpha_{3d}af + \varepsilon_d$$
$$y_{2d} = \beta_{0d} + \beta_{1d}pc + \beta_{2d}itv + \beta_{3d}af + e_d$$

where $y_{1d}$ denotes the magnitude of the $\Delta$Pe at CPz, $y_{2d}$ denotes the magnitude of the $\Delta$Pe at Pz, pc denotes the coefficient for perceived competence beliefs, itv denotes the coefficient for intrinsic task value beliefs, af denotes the coefficient for children's anger/frustration, and $\varepsilon_d/e_d$ are the error terms. The JGLS estimates are presented in columns 1a and 1b of **Table 4**. There was a significant effect of all three motivation variables on the magnitude of the $\Delta$Pe at both CPz and Pz, such that perceived competence beliefs and anger/frustration are related to a larger Pe, and intrinsic task value beliefs are related to a smaller Pe.

Convincing as these results are, one might ask whether these effects would still hold after controlling for demographic variables such as age and gender. We present these results in columns 2a and 2b of **Table 4**. We found that neither age nor gender was significantly related to the magnitude of the $\Delta$Pe (though it should be noted that age was a significant predictor of the Pe on error trials). However, the inclusion of these two covariates did not change the predictive power of each motivation variable, as seen in the magnitude of the coefficients and the standard errors. For both regression models (with and without covariates), for all coefficients where subscript *i* denotes each independent variable, we failed to reject the null hypothesis that $\alpha_{id} = \beta_{id}$, indicating that the significant effects that we find for the three motivation variables are not dependent on electrode site.

**Table 4:** Simultaneous JGLS estimates for motivation variables, child age, and child gender on the ΔPe

| VARIABLES | (1a) ΔPe (CPz) | (1b) ΔPe (Pz) | (2a) ΔPe (CPz) | (2b) ΔPe (Pz) |
|---|---|---|---|---|
| Perceived competence beliefs | 3.076* | 4.535** | 3.244* | 4.592** |
| | (1.417) | (1.421) | (1.425) | (1.438) |
| Intrinsic task value beliefs | -5.635** | -4.281** | -5.779*** | -4.342** |
| | (1.634) | (1.639) | (1.638) | (1.653) |
| Anger / frustration | 1.771* | 2.259** | 1.698* | 2.259** |
| | (0.855) | (0.858) | (0.857) | (0.865) |
| Child age | | | -0.808 | -0.327 |
| | | | (1.220) | (1.231) |
| Child gender | | | -1.242 | 0.043 |
| | | | (2.039) | (2.058) |
| R-squared | 0.288 | 0.303 | 0.298 | 0.304 |

Note: Standard errors in parentheses; *** p<0.001, ** p<0.01, * p<0.05

Note that these regression estimates are more stable and more highly significant compared to the individual regressions presented earlier. Moreover, the high R-squared values indicate that these motivation variables explain a significant portion of the variance in the magnitude of the ΔPe. These results suggest that motivational processes in young children are multifaceted, and that it is very helpful to understand how these motivation variables simultaneously predict the magnitude of the ΔPe rather than exploring each variable separately.

## 4. Discussion

The present study explored how individual differences in young children's motivational characteristics were related to electrophysiological patterns related to errors. We found that children's motivational beliefs and values related to expectancy-value theory were related not to the ERN but to the Pe, and that children's temperamental levels of anger/frustration were also related to the Pe.

### 4.1 Motivation

When assessing children's goal orientations, we found that nearly three out of four children in our sample exhibited a performance goal orientation. This contrasts with research suggesting a roughly equal split between performance goals and mastery goals in preschool-aged children (Smiley & Dweck, 1994; Ziegert et al., 2001), but our findings are consistent with similar work conducted with a recent investigation that used the identical Wedgits puzzle task in a similar preschool-aged sample (Berhenke, 2013). This may be due to important differences in the

challenge puzzle paradigm. In studies that showed an even split between achievement goal orientations, the challenge puzzle paradigm included puzzles that were purposely designed to be unsolvable because of missing pieces. Moreover, these studies used a jigsaw puzzle of cartoon characters, whereas we used three-dimensional blocks. Finally, whereas these studies presented children with an image of the completed puzzle for five to ten seconds, we allowed children to refer to the model card at all times.

*4.2 ERN and Pe*

This study replicates findings from Grammer et al. (2014) suggesting that a reliable and stable ERN and Pe can be generated and observed in preschool-aged children. One important feature of the ERN in young children is that the latency of the ERN is observed earlier than in adult populations. That is, the error-correct difference that defines the ERN seems to begin *before* the zero millisecond mark (before the response is registered). This phenomenon may be attributed to children's slower mean reaction times compared to adults, as well as their still-developing motor skills. Young children may have already cognitively initiated the incorrect response – which is correctly being indexed by the ERN – as the downward movement of the button press has yet to be registered by the acquisition system.

*4.3 Relating motivation and the Pe*

Children's motivational characteristics were related to the Pe but not to the ERN. Recall that the Pe is thought to reflect the conscious awareness of the mistake as well as the emotional response to the mistake. Both theories of the Pe focus on response monitoring processes that may be related not to automatic error detection as indexed by the ERN, but rather to cognitive processes (such as holding and expressing personal beliefs about achievement) associated with a higher-order appraisal of the response and its implications.

*4.3.1 Achievement goal orientations and the Pe*

We found some evidence that children who were learning/mastery oriented had a marginally larger magnitude of the Pe compared to children who were performance oriented. However, a seemingly unrelated regression analysis demonstrated that this finding was highly dependent on electrode site as well as the type of Pe measure used. It may be the case that the way we tweaked

the administration of our challenge puzzle task affected our ability to accurately measure achievement goal orientations. It is also possible that children did not view the successive puzzle designs as harder, but rather as novel or as designs that they simply did not have time to complete. However, it is also plausible that goal orientations related to learning and achievement are simply not as stable during early childhood compared to other aspects of motivation such as competence and value beliefs.

### 4.3.2 Competence beliefs and the Pe

Research indicates that the Pe is comprised of two components; an earlier fronto-central component and a later posterior component. The late Pe may be a P300 associated with the erroneous response (Arbel & Donchin, 2009; Ridderinkhof, Ramautar, & Wijnen, 2009). The P300 reflects attentional processing and subjective expectations about events, and indexes processes related to updating representations in working memory (Donchin, 1981; Polich, 2007). The functional significance of the P300 is important when considering E-V theory, which states that beliefs about one's *current* competence in an activity as well as one's *future* expectations for success are associated with achievement. Because the P300 is associated with updating processes, we might expect that the P300 would be more closely related to future expectations for success rather than beliefs regarding one's current competence. However, within a given domain, children's beliefs about current competence and future expectations of success load onto the same factor (Eccles & Wigfield, 1995), suggesting that expectancy may be a unitary construct in early childhood.

We did not find evidence of an early and late Pe in our study, which suggests that this differentiation may not yet be observable in young children. However, we found that strong beliefs about one's perceived competence were associated with a larger Pe. Children who exhibit strong beliefs about their high ability may be more sensitive to their mistakes. These children may have begun to assimilate a belief of "I am good at puzzles" into their developing sense of self. In this situation, mistakes are problematic as they suggest that an important part of their identity may be called into question. These children may allocate increased attention to their mistakes in order to learn from them so that they can perform at a level that is consistent with their ability beliefs. This is consistent with research suggesting that the P300 is sensitive to

subjective probabilities. If the Pe – particularly, the late Pe – is considered a P300 to the mistake, we might infer that individual differences in subjective expectations about one's performance (i.e., beliefs about one's competence) may explain, at least in part, the variability of the Pe. Children with strong beliefs about their perceived competence would expect to perform well; for these children, the probability of a mistake would be low, leading to a larger Pe or P300 when they do make a mistake.

### 4.3.3 Value beliefs and the Pe

On the other hand, children who expressed strong intrinsic task value beliefs had a smaller Pe. Children who enjoy and like the activity may be much less sensitive to their mistakes on another challenging activity. For these children, the intrinsic enjoyment that they derive from doing puzzles matters more than their actual performance and may therefore pay less attention to their mistakes, as errors do not interfere with their enjoyment of the puzzle activity. This finding should be considered in the context of research demonstrating that the amplitude of the P300 is sensitive to the emotional value of stimuli, such that a larger P300 is associated with greater value (Gray, Ambady, Lowenthal, & Deldin, 2004; Johnston, Miller, & Burleson, 1986). In these studies, value is measured in terms of the individual's subjective utility or value associated with self-relevant stimuli such as hometowns and first names. However, in the present study, we conceptualized value as children's level of enjoyment on a puzzle activity and related that to neutral animal images in the Zoo Game. In other words, the Pe effect that we observed was not related to specific responses to self-relevant targets, but rather reflected a more generic measure of "value." Our results present an alternative way to conceptualize value in terms of trait-like motivational processes.

### 4.3.4 Anger and frustration: The role of achievement-related emotions

The affective processing theory of the Pe suggests that this component reflects, at least in part, the emotional response associated with the appraisal of the mistake. We found that children who had higher levels of temperamental anger and frustration as reported by their parents had a larger Pe. We focused on anger/frustration given previous research suggesting that these affective processes may often accompany goal-directed behavior especially in challenging activities or situations. Recall that this subscale is defined as the "amount of negative affect related to

interruption of ongoing tasks or goal blocking." Our finding suggests that it is not just any emotional response that is indexed by the Pe, but rather a specific temperamental profile – anger/frustration – that is closely associated with motivational processes. This interpretation is supported by the fact that children's anger/frustration was not significantly related to the other motivational constructs that were assessed, as well as our regression findings demonstrating that anger/frustration had a unique impact on the variability of the Pe over and above the effects of perceived competence and intrinsic task value beliefs. Our findings demonstrate that beliefs and achievement-related emotions may act in part as independent mechanisms that modulate the Pe.

*4.4 Limitations and directions for future research*

The variability in our perceived competence and intrinsic task value measures was limited; the range of scores on each measure was between two and four (out of four), with no child scoring a zero or one on either measure. Although previous research has shown that young children's competence beliefs tend to be very positive (e.g., Stipek & Greene, 2001), our finding was unexpected given previous research demonstrating greater variability in a sample of similar aged children using the same measure (Berhenke, 2013). Despite the limited variability within each measure, it is important to note that we still found that each set of beliefs was significantly related to the magnitude of the Pe.

We assessed children's motivational beliefs on a challenge puzzle activity and then related those beliefs to the ERP components that were generated from a different activity – the Go/No-Go Zoo Game. Given our data, we were unable to determine whether children's beliefs were consistent across both activities. However, there are reasons to believe that they might be very similar. Research suggests that elementary-aged children have distinct beliefs about what they are good at and what they value in different achievement domains (Wigfield & Eccles, 2000). However, children without any formal schooling and those who are relatively new to the formal school environment – such as the preschool, kindergarten, and first-grade children in our sample – may hold more domain-general beliefs about their perceived competence and intrinsic task value across different activities. Because of this, it is likely that children's beliefs would have been consistent across both the challenge puzzle activity as well as the Zoo Game. Nevertheless, future research should assess children's motivational beliefs on a variety of activities – including

the Go/No-Go task – in order to explore whether these competence and value beliefs are domain-general or domain-specific in this age range.

Finally, our anger/frustration findings must be understood in a broader context. Although we found a consistent pattern of effects of anger/frustration on the magnitude of both the ERN and the Pe, we do not know if there are other temperamental profiles that would also explain the variability in these two ERP components. Moreover, whereas achievement goal orientation and competence and value beliefs were measured using direct child assessments, children's anger/frustration was measured using a parent report. We might expect a different pattern of results if we had assessed children's emotions directly (e.g., through observations or controlled laboratory episodes). Nevertheless, because parents often have better knowledge about their children's behaviors in a wide range of real-world settings and situations, parent reports of children's temperament still provide an important, global perspective on children's affective processes.

## 5. Conclusion

This study confirms findings from recent research suggesting that electrophysiological phenomena related to error processing can be reliably measured and observed in children as young as four years of age. Moreover, individual differences in young children's motivational beliefs and achievement-related emotions are related to the error positivity, suggesting that the Pe reflects the conscious awareness of the error as well as the emotional response associated with the appraisal of the mistake. Interestingly, the same beliefs and emotions were not associated with the ERN in young children. Exploring cognitive processes related to motivation such as metacognition may provide additional insights about how children's abilities to reason about their own thinking can affect how they respond to and interpret their mistakes.

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**Chapter III**

**Schooling effects on behavioral and academic skills and electrophysiological components of error processing: An exploratory regression discontinuity analysis**

**Abstract**

The impact of schooling on children's early behavioral and academic skills has been well documented. However, less is known about the potential effect of schooling on ERP components related to executive functioning and motivation, such as the error-related negativity (ERN) and error positivity (Pe). The ERN reflects automatic error detection processes used to increase cognitive control, and the Pe is related to an individual's conscious awareness of and attention to an erroneous response. The Pe is also sensitive to individual differences in motivational beliefs and emotions. Because classrooms provide a setting in which children learn to monitor their responses and learn from their mistakes, electrophysiological indices associated with response monitoring may be uniquely influenced by schooling. 113 three- to seven-year-old children participated in two brain-behavior studies that explored executive functioning, motivation, and early academic skills. A regression discontinuity (RD) design was used to explore schooling effects. There was an effect of one full year of kindergarten schooling on children's early literacy skills, as well an effect approaching trend level on children's early math skills. When looking at behavioral measures of inhibitory control, there was an effect on children's reaction time on error trials on a Go/No-Go task, which was present only in girls. There were no schooling effects on the ERN or Pe. This paper focuses primarily on how RD can be implemented in a child ERP study, and includes a discussion on methodological challenges and solutions.

**1. Introduction**

Entry to formal schooling constitutes an important developmental milestone in a child's life. Children are introduced to classroom teachers, other school staff members, and same- and different-age peers. Children also experience new activities, particularly formal academic

instruction and assessment. Executive functioning (EF) and motivation have been shown to be important for school success. Teachers report that nearly half of all entering kindergarten children do not experience a successful entry to school, with "difficulty following directions" being cited as a specific problem by nearly half of all kindergarten teachers in a nationally-representative survey (Rimm-Kaufman, Pianta, & Cox, 2000). Children's EF skills – which include the ability to follow rules and directions and more broadly reflect cognitive processes that are crucial for successful, goal-directed behavior – predict math and reading outcomes in kindergarten and beyond (Blair & Razza, 2007; McClelland et al., 2007). Turning to motivation, students for whom engaging in the activity is its own reward – that is, those who are intrinsically motivated – have more positive academic outcomes than individuals who are primarily extrinsically motivated by a tangible reward or outcome (Lepper, Corpus, & Iyengar, 2005). Students' beliefs about their expectations for success in math are stronger predictors of math achievement than previous math outcomes (Meece, Wigfield & Eccles, 1990), and motivational characteristics may be related to children's early reading outcomes (Berhenke, 2013).

How do children develop strong EF skills and adaptive patterns of motivation? General maturational factors account for part of the growth. Growth in EF skills is associated with concomitant maturation of the prefrontal cortex, a brain area responsible for executive, higher-order cognitive processes (e.g., Diamond, 2013). Research on the neural basis of motivation has traditionally used imaging techniques to pinpoint the brain areas that are associated with motivated behavior. Areas of dorsolateral prefrontal cortex are involved in integrating motivational and EF processes and goal pursuit more generally (Spielberg et al., 2012), and greater motivation to learn is correlated with increased bilateral activity in the putamen (Mizuno et al., 2008). Less is known about the electrophysiological correlates of motivation in younger populations. In addition to biological maturation, does schooling have a unique effect on children's developing EF and motivation? That is, is there any "value added" by schools and classrooms on the development of these skills and if so, how large are these effects? The purpose of this study is to explore whether early schooling experiences have a unique impact on these processes, as well as to estimate the magnitude of this impact if it exists.

*1.1 Measurement of EF and motivation*

*1.1.1 Executive functioning*

Children's EF skills have been measured in various ways. Assessments include the Dimensional Change Card Sort, Head-Toes-Knees-Shoulders, Day/Night, Bear/Dragon, Pencil Tap, Gift Delay, Delay of Gratification (the "marshmallow test"), Woodcock Johnson Pair Cancellation, among others (e.g., Ponitz, McClelland, Matthews, & Morrison, 2009; Carlson, 2005). There have been two primary challenges associated with measuring EF in preschool children. First, it is often difficult to pinpoint the underlying construct being assessed. EF is comprised of three subprocesses, including cognitive flexibility (or attention), inhibitory control (or response inhibition), and working memory. Research suggests that these subprocesses comprise a unitary EF factor in young children which then differentiates as children get older (Miyake & Friedman, 2012; Wiebe, Espy, & Charak, 2008). However, some assessments are thought to measure one particular subprocess to a greater extent than another, while other assessments capture the global nature of EF. Second, many of these tasks often suffer from floor and ceiling effects. Because EF skills develop rapidly during the preschool and early elementary years, children who differ in age by just one or two years can experience dramatically different outcomes. Using one measure for younger children and another measure for older children makes it difficult to equate children's EF skills in a coherent way. These considerable theoretical and methodological challenges have prompted some researchers to refer to these issues as "conceptual clutter" and "measurement mayhem" (Morrison & Grammer, in press).

*1.1.2 Motivation*

Motivation has been studied from different theoretical perspectives. Achievement goal theory focuses on the reasons for engaging in an activity. Individuals with learning or mastery orientations focus on increasing competence, whereas individuals with performance orientations focus on validating or confirming pre-existing notions about ability (Dweck, 2003; Dweck, Mangels, & Good, 2004). Separately, expectancy-value theory focuses on how an individual's beliefs about her perceived competence and the degree to which she likes or values the activity influence achievement (Wigfield, Eccles, Schiefele, Roeser, & Davis-Kean, 2006).

Similar measurement issues abound when exploring children's early motivation. Because motivation is often defined as a set of beliefs, values, and emotions that influence how an individual tackles an activity or goal, young children often do not have the cognitive capability to accurately reflect on these features of the self or cannot articulate them fluently or completely (e.g., Ruble, Parsons, & Ross, 1976). In order to circumvent this problem, researchers have often observed and coded children's behaviors as they engage in a challenge puzzle activity. Children's preferences for engaging in a challenging versus non-challenging activity have been shown to be associated with different achievement goal orientations (Smiley & Dweck, 1994). Turning to expectancy-value theory, children possess beliefs about their abilities (or perceived competence) and what they value or enjoy (or subjective task value; Wigfield & Eccles, 2000). Previous studies have used a puppet interview paradigm to assess young children's beliefs about their abilities and what they like and enjoy (Berhenke, 2013; Kim, Marulis, Grammer, Morrison, & Gehring, in preparation). Despite these examples, the vast majority of studies of motivation have focused on adolescent youth who are better able to report on aspects of the self.

*1.2 EF, motivation, and children's mistakes*

Increasing attention has been devoted to understanding the neural correlates of EF and motivation. The event-related potential (ERP) technique has been used to explore the timing of cognitive processes in the young child's brain. A major advantage of this technique is that it can record brain activity even in the absence of any observable behavior. Observable behavior may be preceded by hidden but meaningful changes in neural functioning that can be measured using the ERP technique.

Both EF skills and motivation are particularly important during challenging activities. Being able to flexibly shift attention and strategies based on the situation, exercising self-control, remembering multi-step rules and directions in the face of distractions, and holding a belief that a goal is attainable rather than engaging in helpless cognitions, are aspects of EF and motivation that are crucial for success. However, even the strongest EF skills and adaptive motivational patterns of behavior will occasionally fail, and individuals will make mistakes along the way. Exploring how children respond to their mistakes can potentially yield important insights into the nature of EF and motivation. In this study, we used the event-related potential (ERP) technique

to explore specific patterns of brain responses associated with error processing as a way to better understand the nature of EF and motivation in young children.

*1.3 Error-related negativity (ERN), EF, and academic outcomes*

The error-related negativity (ERN) is seen as a negative-going deflection in an ERP waveform occurring about 50 milliseconds following an incorrect response on a speeded target discrimination task. The ERN is present in children as young as three years of age with little evidence for age-related changes in ERN amplitude before age seven (Grammer, Carrasco, Gehring, & Morrison, 2014). The ERN is generated by the anterior cingulate cortex, a brain area implicated in cognitive control and executive functioning processes (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Coles, Meyer, & Donchin, 1990; Gehring, Goss, Coles, Meyer, & Donchin, 1993; see Gehring, Liu, Orr, & Carp, 2012, for a review). Theoretical accounts of the ERN include reinforcement learning (Holroyd & Coles, 2002) and conflict monitoring perspectives (Larson, Clayson, & Clawson, 2014; Yeung, Botvinick, & Cohen, 2004). Both models suggest that the ERN is related to error detection and that these detection processes are utilized to increase cognitive control (Hajcak, 2012). The ERN may be related to individual differences in EF (e.g., Lyons & Zelazo, 2011). Specifically, researchers have speculated that a larger ERN reflects improved action monitoring and top-down cognitive control mechanisms that may facilitate success in various domains, particularly academic achievement (Hirsh & Inzlicht, 2010).

*1.4 Error positivity (Pe), motivation, and academic outcomes*

The Pe accompanies the ERN and is observed at centroparietal electrode sites, occurring about 200 to 500 ms after an incorrect response (Gehring et al., 2012). The error-awareness hypothesis suggests that the Pe reflects processes underlying the subject's conscious awareness and recognition of the error, whereas the affective processing hypothesis suggests that the Pe reflects the emotional response associated with the awareness of the mistake (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). Moreover, the Pe has been shown to be sensitive to individual differences in motivational beliefs about ability and task value and achievement-related emotions such as anger and frustration (Kim et al., in preparation), as well as individual differences in ability mindsets (Moser et al.,

2011). Recent research has demonstrated a positive correlation between age and the magnitude of the Pe in young children, suggesting that the Pe may index aspects of development related to error processing such as processes underlying executive functions or other higher-order cognitive processes (Grammer et al., 2014). The Pe – particularly the late Pe – may be a stimulus-locked P300 to the erroneous response (Arbel & Donchin, 2009; Ridderinkhof, Ramautar, & Wijnen, 2009). Research has demonstrated that the P300 is related to early math and reading outcomes, which suggests that the late Pe or P300, as a measure of attentional processes involved in inhibitory control, may also be related to aspects of EF (Hillman et al., 2012). In summary, there is evidence to suggest that the ERN and Pe, which index aspects related to EF and motivation, may be related to academic outcomes.

*1.5 Schooling effects on EF and motivation*

EF skills are often learned in school settings. Evidence-based programs such as Tools of the Mind, Promoting Alternative Thinking Strategies (PATHS), and Chicago School Readiness Project (CSRP), focus on developing children's self-regulation through various classroom activities and pedagogical strategies (Diamond, Barnett, Thomas, & Munro, 2007; Diamond, 2012; Domitrovich, Cortes, & Greenberg, 2007; Raver et al., 2011). Motivation can also be shaped in schools and classrooms. The increased social comparison that children engage in, along with the greater focus on evaluation and comparison in academic contexts, shape growth of motivation during the schooling years (Wigfield & Eccles, 2002). Children's experiences with successes and failures, particularly the social disapproval and sanctions associated with failures, likely increase once children enter formal schooling, thereby shaping motivational beliefs and values (Ruble, Parsons, & Ross, 1976). Teacher support and teacher-student interactions are also related to the development of motivational processes (Ryan & Patrick, 2001). Given research demonstrating that EF and motivation are related to school success, it is important to better understand the nature and development of these cognitive processes.

A study using a regression discontinuity (RD) design found that children who attended preschool experienced higher scores on reading, spelling, and math compared to same-age peers who did not have any preschool experience (Gormley, Gayer, Phillips, & Dawson, 2005). Studies using an analysis method called the school cutoff technique (SC), a variant of the RD design, have also

found similar effects on early academic and behavioral outcomes. Marie Burrage and her colleagues found that children with preschool experience had better outcomes on a word decoding task and a working memory task compared to same-age children who had no preschool experience. The authors also found a trend level schooling effect of preschool experience on a measure of response inhibition (Burrage et al., 2008). In a similar study, Lori Skibbe and her colleagues found a preschool schooling effect for decoding and letter knowledge performance, but did not find evidence of a schooling effect for children's vocabulary and self-regulation outcomes (Skibbe, Connor, Morrison, & Jewkes, 2011). The present study seeks to address a gap in the research literature by exploring whether schooling experiences have a unique impact on the *electrophysiological* processes underlying children's EF, motivation, and early academic skills by implementing a RD design.

*1.6 The present study*
Because our participants span three to seven years of age (from preschool through first grade), we are able to explore two schooling effects: (1) the effect of preschool compared to a no preschool comparison group and (2) the effect of kindergarten schooling compared to a no kindergarten (or preschool only) comparison group. Unless otherwise specified, "schooling" or "schooling effect" refers to a generic schooling effect. We had three research questions:

1. Is there a unique effect of schooling on early reading and math outcomes? *Prediction:* We expected to find a schooling effect on early reading outcomes, consistent with previous work exploring schooling and literacy in this age group. Because math instruction in preschool and kindergarten classrooms is limited compared to time spent in literacy activities (e.g., Kim, Bell, & Morrison, 2011), we did not expect to find a significant schooling effect on early math outcomes in our sample.
2. Is there a unique effect of schooling on behavioral measures of inhibitory control? *Prediction:* We expected to find a schooling effect on our behavioral measures of inhibitory control. Specifically, we expected schooling to be associated with better accuracy and lower error rate on the Go/No-Go response inhibition task. Error rate may be a more valid measure of inhibitory control compared to accuracy, as withholding the prepotent response to an infrequent No-Go target may better reflect EF skills compared to

responding to a frequent Go target. We also predicted that schooling to lead to quicker reaction times on both correct and error trials. Being able to successfully withhold responses in challenging situations reflects EF skills, and schooling may provide formal and informal opportunities to practice and improve these skills.

3. Is there a unique effect of schooling on ERP measures of EF and motivation – ERN and Pe? *Prediction:* We expected to find a schooling effect on both the ERN and Pe, such that schooling would be related to a larger (more negative) ERN, which reflects a more mature and efficient cognitive control mechanism. Turning to the Pe, this component is thought to reflect attentional and motivational processes associated with response monitoring. In the context of structured academic activities and assessment in the school setting, children may have formal and informal opportunities to develop a greater awareness of their responses and how to respond appropriately to them, particularly their mistakes. Therefore, we predicted that schooling would also be related to a larger Pe.

## 2. Method

### 2.1 Participants and procedure

Participants and procedures are explained in detail in both Grammer et al. (2014) as well as Kim et al. (in preparation) and in Chapter II of this dissertation; therefore, a brief explanation is presented here. 113 participants between the ages of three and seven were drawn from the laboratory-based and school-based brain-behavior studies. A comparison of key features in the lab study and school study are presented in **Table 5**.

| Table 5: Comparing the lab study and the school study | | |
|---|---|---|
| Feature | Lab study | School study |
| Number of children | 50 | 63 |
| Grade level breakdown | Preschool = 26<br>Kindergarten = 12<br>First grade = 12 | Preschool = 2<br>Kindergarten = 37<br>First grade = 24 |
| Age breakdown | Four years old or younger = 21<br>Five years old = 17<br>Six years old or older = 12 | Four years old or younger = 3<br>Five years old = 30<br>Six years old or older = 30 |
| Data collection period | 2011-2012, 2012-2013, and 2013-2014 | 2011-2012 |
| Timing of assessments | Throughout the entire calendar year | Fall (especially October and November) and spring (especially April and May) |
| Study procedures | Behavioral and ERP testing conducted in the lab in one visit | Behavioral and ERP testing conducted at the school in two visits |
| Zoo Game | Used first version of the Zoo Game (without the map) | Used second version of the Zoo Game (with the map) |
| Baseline correction | -300 to -200 ms | -200 to -100 ms |
| ERN window | -50 to 50 ms | 0 to 50 ms |
| Pe window | 200 to 500 ms | 200 to 500 ms |

*2.2 Assessments*

Both studies administered the Letter-Word Identification and the Applied Problems subtests from the Woodcock Johnson Tests of Achievement III (WJ-III; Woodcock & Mather, 2001). The letter-word identification subtest assesses children's early decoding and literacy skills through identification of letters and words. The applied problems subtest assesses children's problem solving skills through arithmetic word problems.

*2.3 Go/No-Go Task*

A description of the task is provided in Chapter II of the dissertation in Section 2.4. The task was identical except for the following: School study children who were assessed in the spring played a version of the Zoo Game that included a map of the zoo and other superficial features not present in the original game. Importantly, this version retained the same number and ratio of Go and No-Go stimuli as well as the same timing of stimuli and interstimulus intervals.

*2.4 Electrophysiological recording*

A description of the details of the electrophysiological recording is provided in Chapter II of the dissertation in Section 2.5. All details are identical except for the following: After an examination of the grand average waveforms for the combined sample of lab study and school study children, we concluded that the time windows used in the school study were most

appropriate for the combined sample. 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. 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., Fz, FCz, Cz, CPz, Pz). Statistical analyses were conducted using Stata 13.1.

## 3. Assessing schooling effects

### 3.1 School cutoff technique and regression discontinuity

Two quasi-experimental methods are commonly used to explore schooling effects. One of these methods, the school cutoff technique (SC), capitalizes on the arbitrary cutoff date in school districts that determine whether a child is eligible to enroll in kindergarten that year. In school districts with a December 1 cutoff date, a child must be born on or before December 1 in order to be eligible to enroll in kindergarten for that same academic year. Children born on December 2 or later must wait a year before enrolling in kindergarten. This school entry cutoff date allows researchers to compare outcomes for same-age children born just before and just after the cutoff, and therefore to determine whether kindergarten schooling has a unique impact on outcomes. In the SC technique, children are eligible for the study if the child has a birth date within two months of the cutoff date (Morrison, Smith, & Dow-Ehrensberger, 1995). An important assumption of SC is that children born in the two-month window before the cutoff date are not significantly different from the children born in the two-month window after the cutoff date. **Figure 9** depicts a hypothetical SC graph. In this graph, the jump at the cut point suggests that the schooling experienced by first grade children has a significant effect on outcomes than the schooling experienced by their same-age kindergarten peers.
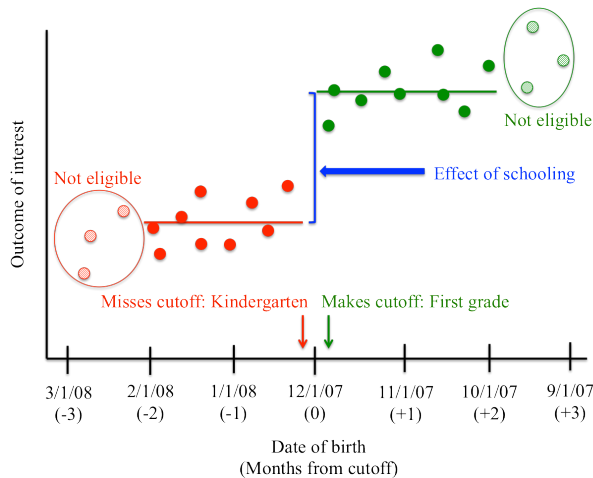
**Figure 9:** Hypothetical school cutoff graph

In both methods, children can be assessed at the beginning of the school year and at the end of the school year. For example, let us say that we have two groups; one group comprises first grade children who just made the cutoff for first grade entry, and the second group comprises current kindergarten children who just missed the cutoff for kindergarten entry the previous year. If these first grade children have better outcomes than their same-age kindergarten peers in the fall, we can conclude that the kindergarten schooling experiences of first grade children have a unique effect. By exploring how both groups change from fall to spring, we can also explore the magnitude of change that is due to biological maturation as well as whether the two groups experience different rates of change in their outcomes. For example, if the gap between first graders and kindergarten children is larger in the spring compared to the fall, this suggests that first grade schooling has a greater impact on outcomes compared to kindergarten schooling.

*3.2 Drawbacks of the school cutoff technique*

One major drawback is that the SC technique severely constrains the selection of participants. Ideally, children must be born within two months of the cutoff entry date in order to be eligible for the study. (Interpretations would be problematic if the two groups differed too much in average age, as the assumption that children within the four-month window are similar enough to be grouped together would start to break down. While the pre-academic skills of children born within two months of each other may be similar, other outcome variables may exhibit substantial variability within such a narrow time frame.) This constraint imposes considerable logistical

challenges for researchers, as not all children who return signed consent forms will be eligible for the study. As shown in **Figure 9**, children born in months February and September (and months in between) would be ineligible for the study; that is, only one-third of children would potentially be eligible for the study. Because of this, researchers often need to recruit multiple cohorts of participants over multiple years in order to achieve the sample size necessary to detect effects.

*3.3 Regression discontinuity: An alternative approach*

Regression discontinuity, or RD, also capitalizes on an arbitrary cut point that divides individuals into two groups. Just like the school cutoff method, which is considered to be a variant of the RD approach, the entry date for kindergarten entry serves as the cut point. However, unlike the school cutoff method, RD does not impose any constraints on eligibility; all children can be included in a RD analysis even if the child is born outside the four-month window of eligibility. In RD, we can use all observations as long as we control for the running variable, which is a variable that captures how far the child is from the cut point. *Months from cutoff* is the running variable that determines which group the child belongs in (e.g., kindergarten or first grade) and where in each group the child is located (close or far from the cut point) based on the child's month of birth. Controlling for this variable allows children's outcomes to vary depending on how close or far they are from the cut point; children close to the cut point have different outcomes compared to those further away from the cut point. This allows us to estimate the jump without bias. On the other hand, without controlling for the running variable, we would in effect have a SC method, which assumes that children experience the same outcomes regardless of how far away they are from the cut point. In this way, RD allows the user to use all observations and can therefore potentially reduce the considerable logistical constraints associated with recruitment.

However, there are some caveats. One requirement of RD is that in exchange for using all observations, there needs to be a sufficient sample size in each group in order to be able to detect effects, particularly in the close vicinity of the cut point. Because RD, like the SC technique, attempts to measure the "jump" or discontinuity at the cut point due to a schooling effect, there

must be enough observations on either side of the cut point in order to accurately estimate this jump. Otherwise, the estimation of the best-fit regression line may be biased.

In the current study, we did not have enough children born in the four-month window of eligibility which is necessary for the SC technique. In the lab study, only 13 out of 50 children (26.0%) were eligible for the school cutoff analysis. In the school study, only 19 out of 63 children (30.2%) were eligible for the analysis. Moreover, in the lab study, children were assessed only once during the school year, whereas children in the school study were assessed in both the fall and the spring. These features of both the lab study and the school study make RD the preferred method to explore schooling effects compared to SC.

## 4. Regression discontinuity: Considerations and challenges

### 4.1 Multiple cut points

In the lab study, data were collected in three waves: during the 2011-2012, 2012-2013, and 2013-2014 school years. In the school study, data were collected only during the 2011-2012 year. While the cutoff date for kindergarten entry was December 1 for the 2011-2012 and 2012-2013 years, the State of Michigan moved the cutoff date to November 1 for the 2013-2014 year. This does not pose any problems for two reasons. First, the study procedures were identical across years, and we are unaware of any major policy changes that would have made the school experience considerably different across these years. Second, in RD, the correct calculation of the running variable on the x-axis is crucially important. Because the running variable is defined as "months from cutoff," it does not matter that the cutoff entry date was shifted by one month, as the absolute date is not important but rather the location of each individual child relative to the cutoff entry date. Calculation of the running variable is discussed in Section 5.1.

### 4.2 Parametric versus non-parametric model

In RD, one has the option to use a parametric (global) or a non-parametric (local) model. In a parametric model, all observations – those that are furthest from the cut point as well as those closest to the cut point – are used to model the outcome for each group. In a non-parametric model, only the observations that are closest to the cut point are used to estimate the jump (Bloom, 2009; Jacob, Zhu, Somers, & Bloom, 2012). Regardless of the model that is used, it is

important that there are enough data points in the immediate vicinity of the cut point because those observations are most influential in estimating the jump. Having too few or no children near the cutoff point – that is, not having enough children born in November and December for a December 1 cutoff date – would bias our estimates. We will return to this topic in Section 6.2 in our discussion of child age, where we will show that this is not an issue in our combined sample. Because our overall sample sizes are small in the context of RD, we will use a parametric or global strategy in order to take advantage of all observations. In fact, it is generally the case in preschool age-cutoff RD studies that a parametric model is used because the number of observations near the cut point is too few to justify a local model (Lipsey, Weiland, Yoshikawa, Wilson, & Hofer, 2014).

*4.3 Fuzzy versus sharp design: Kindergarten redshirting and other grade level considerations*
In a sharp design, it is assumed that all children who are eligible for the treatment (in this case, school entry based on the cutoff date) actually receive the treatment, and that all children who are not eligible for the treatment do not receive it. That is, it is assumed that there are no crossover effects. However, this may not be a valid assumption when considering kindergarten enrollment. Research suggests that "academic redshirting" may occur; for children who are eligible for kindergarten enrollment but are born quite close to the cutoff date, parents may decide to postpone enrollment for another year due to the child's age and temperament or the parents' personal philosophy (Noel & Newman, 2003). In addition, under the new kindergarten cutoff date policy, parents in Michigan were able to apply for a waiver that would allow their children to enroll in kindergarten under the older, late cutoff date. This would lead to treatment crossover, which would make it difficult to interpret a RD analysis in the conventional way.

A related issue concerns the correct identification of a child's grade level. For children in the lab study who were assessed near the end of the child's school year and during the summer months, it is not immediately obvious as to which grade level the parent reported for the child. For example, for kindergarten children assessed in June (the last month of the school year) and the subsequent summer months, parents may well have reported their children as being in first grade – that is, the grade that the child will be entering in the fall – rather than the grade that the child had just completed. Without a careful consideration as to whether the grade level was accurately

reported for each child, children may end up in the wrong groups, which would lead to inaccurate RD estimates. For purposes of RD, I argue that the child's grade should be increased only when the child begins the new school year. That is, children who are assessed between June and August should be labeled as being in the grade the child just completed.

In the lab study, I calculated the grade that the child should have been enrolled in at the time of assessment based on the child's date of birth. This yielded a list of ten children whose reported grade did not match these calculations; five children were enrolled in one lower grade (presumably redshirted), and five children were enrolled in one higher grade. When examining the five children who were enrolled in one higher grade, all of these children were assessed in June and August. Therefore, consistent with my prediction, it is likely that parents wrote down the child's next grade level rather than the grade that the child was just completing or had completed. For these children, their grade level was adjusted downward.

After cross-referencing with the open-ended enrollment data provided by parents, three of the five lower-grade children were indeed redshirted:

1. Age = 5.2 years, in preschool: "She had an early September birthday. We wanted her to be 5 going on 6y instead of 4 going on 5y when she started kindergarten."

2. Age = 5.3 years, in preschool: "Needed an additional year in young 5's program to develop socially to be prepared for kindergarten. I also preferred for [name] to be one of the older students in his class rather than one of the youngest. Having the year in young 5's helped [name] increase his confidence and be a leader on his kindergarten class."

3. Age = 6.4 years, in kindergarten: "I enrolled him when he was 5 & turning 6 at the end of the September 2011 that he started kindergarten."

In conclusion, there is some evidence that there was treatment crossover in the lab study, at least for children who were eligible for kindergarten but their parents opted to hold them back one year. Technically speaking, any evidence of crossover would be considered a fuzzy design and the RD analysis would be adjusted accordingly. However, given the small sample size and the exploratory nature of this study, we decided to proceed with a sharp design as the analysis would be much more simplified and easier to illustrate.

*4.4 Functional form: Linear or curvilinear regression?*

Functional form represents the nature of the relation between the independent variable(s) and the dependent variable. In many analyses, the functional form between two variables is often assumed to be linear; that is, the dependent variable changes at a constant rate depending on the value of the independent variable. However, there are other instances in which the appropriate functional form is not linear but rather curvilinear, for example, a quadratic relation. As in other regression frameworks, specifying the correct underlying functional form of the relation between the running variable (months from cutoff) and the outcome variable is crucial in order to estimate nonbiased treatment effects in RD.
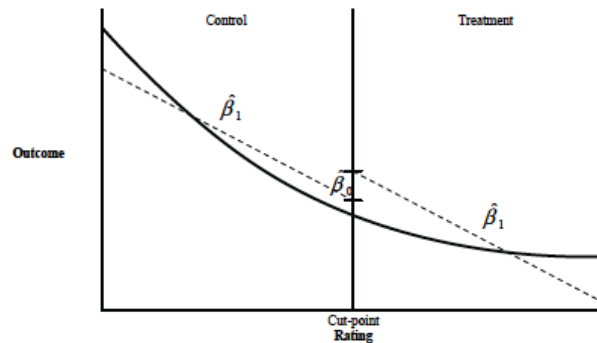


**Figure 10:** Regression discontinuity estimate with an incorrect functional form. Reproduced from Jacob et al. (2012)

**Figure 10** demonstrates how an incorrect functional form can lead to biased effects. In this example, the functional form was assumed to be linear, as shown in the dashed lines. Based on this assumption, there seems to be a jump at the cut point, implying a treatment effect. However, the true functional form is actually a curvilinear relation, as shown in the solid line, in which the dependent variable falls at a decreasing rate as a function of the independent variable. In this case, there is actually no jump at the cut point; assuming a linear functional form leads us to estimate a treatment effect when in actuality there is none. A linear functional form appears to be a reasonable approximation to our data and we do not have the sample size to calculate a non-linear functional form. Therefore, in our analysis, we assume that the functional form between our variables of interest is linear.

A similar concept is that of bandwidth. In Jacob et al. (2012), bandwidth is defined as the space in close vicinity to the cut point. A larger bandwidth takes into account a greater number of observations (not limited to observations near the cut point) and thus the estimates become more precise; however, a larger bandwidth also introduces a greater potential for bias. A smaller bandwidth will include just the observations close to the cut point and therefore reduces bias, but the estimates may not be as precise. A larger bandwidth is associated with estimating linear regression estimates, whereas a smaller bandwidth is associated with local polynomial regression estimates in which the best-fit line may be curvilinear. In our analysis, we will select a bandwidth that is large enough to generate linear estimates in order to use as many observations as possible (given our small sample size), while acknowledging that this may lead to biased estimates.

## 5. Implementing RD: RD in graphical form

Along with the SC technique, RD relies more heavily on the interpretation of graphs compared to other conventional statistical techniques. **Figure 11** depicts a hypothetical RD graph that shows a schooling effect. Note the similarities and differences between this figure and the hypothetical SC graph in **Figure 9.** Both methods use the jump at the cut point to estimate the effect of schooling. However, while the SC technique assumes that children within the two-month window are equivalent enough to be treated as one group, RD uses all of the observations in order to estimate a best-fit regression line for each group. As shown in the figure, we would expect each of these regression lines to have a positive slope, as older children should have stronger outcomes compared to younger children. Another important difference is that while children are only eligible for the SC study if they are born within two months of the cutoff entry date, this constraint is not applicable in RD.
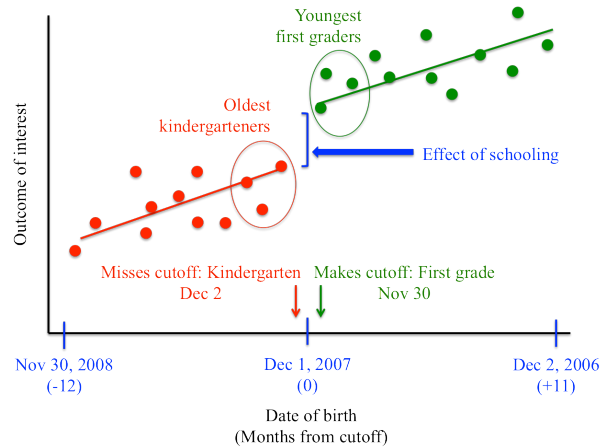
**Figure 11:** Hypothetical RD graph

*5.1 Computing the running variable*

Correctly computing the running variable is crucial for the RD analysis, so I present detailed information that shows how this variable was computed. As introduced in Section 3.3, the running variable – always plotted on the x-axis – is the variable that determines which group (e.g., kindergarten or first grade) the child belongs in, and where the child is located within each group. In RD, we are interested in determining how far the child is from the cut point based on the child's date of birth. Our running variable, "months from cutoff," goes from -12 to -1 for the lower grade comparison group, and 0 to 11 for the older grade comparison group. We denoted 0 as the value at which the jump occurs; a child with a value of 0 just made the cutoff (e.g., child was born between November 1 and December 1 for a December 1 cutoff date). A child with a value of -1 just missed the cutoff; the child was born one month *after* the cutoff (e.g., child was born between December 2 and December 31) and is therefore in the lower grade comparison group. Note that the preschool children always have a negative number because they are always the lower grade comparison group, and that the first grade children always have a zero or positive number because they are always the older grade comparison group. The kindergarten children have a negative or zero/positive number depending on whether they are compared with the preschool group or the first grade group. **Table 6** shows all the possible values for the running variable depending on the child's month of birth. **Table 7** illustrates how the running variable was computed for several children.

| Table 6: Values of the running variable: Months from cutoff | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Month of birth | Cutoff date: December 1 | | | | Cutoff date: November 1 | | | |
| | Pre-K | K (vs. Pre-K) | K (vs. 1st) | 1st | Pre-K | K (vs. Pre-K) | K (vs. 1st) | 1st |
| | Months from cutoff | | | | Months from cutoff | | | |
| 1 | -2 | +10 | -2 | +10 | -3 | +9 | -3 | +9 |
| 2 | -3 | +9 | -3 | +9 | -4 | +8 | -4 | +8 |
| 3 | -4 | +8 | -4 | +8 | -5 | +7 | -5 | +7 |
| 4 | -5 | +7 | -5 | +7 | -6 | +6 | -6 | +6 |
| 5 | -6 | +6 | -6 | +6 | -7 | +5 | -7 | +5 |
| 6 | -7 | +5 | -7 | +5 | -8 | +4 | -8 | +4 |
| 7 | -8 | +4 | -8 | +4 | -9 | +3 | -9 | +3 |
| 8 | -9 | +3 | -9 | +3 | -10 | +2 | -10 | +2 |
| 9 | -10 | +2 | -10 | +2 | -11 | +1 | -11 | +1 |
| 10 | -11 | +1 | -11 | +1 | -12 | 0 | -12 | 0 |
| 11 | -12 | 0 | -12 | 0 | -1 | +11 | -1 | +11 |
| 12 | -1 | +11 | -1 | +11 | -2 | +10 | -2 | +10 |

| Table 7: Examples of how running variable values were assigned | | | | | |
|---|---|---|---|---|---|
| ID | Grade | Year assessed | DOB | Running variable | Why? |
| 101 | Pre-K | 2011-2012 | 12/19/2006 | -1 | Missed cutoff by one month (born December 19 vs. December 1 cutoff date) |
| 106 | K | 2011-2012 | 2/3/2006 | Pre-K vs. K comparison: +9<br><br>K vs. 1st comparison: -3 | Made cutoff by 9 months (Feb vs. Dec of the same year)<br><br>Missed cutoff by 3 months (Feb vs. Dec of previous year) |
| 107 | 1st | 2011-2012 | 5/22/2005 | +6 | Made cutoff by 6 months (May vs. Dec of the same year) |
| 151 | K | 2013-2014 (cutoff date is Nov 1) | 2/10/2008 | Pre-K vs. K comparison: +8<br><br>K vs. 1st comparison: -4 | Made cutoff by 8 months (Feb vs. Nov of the same year)<br>Missed cutoff by 4 months (Feb vs. Nov of the previous year)<br>Compare with ID 106 who was born in the same month but cutoff date is different. |

## 5.2 Sorting observations into bins

In RD, children do not occupy an infinite number of spaces on the x-axis depending on their date of birth. By choosing a running variable of "months from cutoff," children born in the same month occupy the same space on the x-axis. Therefore, for purposes of our RD, a child born on March 1 is treated the same as a child born on March 31. (Both of these children would have the same value of the "months from cutoff" running variable.) In other words, the data are organized into month bins. Depending on the data set, it may be appropriate to either narrow or widen the width of the bin. The advantage of narrower bins is that the estimation of the regression can be

more precise. However, with a smaller sample size, narrow bins may not make sense, as there may be many bins that contain very few or even no observations. A wider bin width is advantageous in that each bin will have a good number of observations, but the precision of the estimates will be reduced. This is analogous to estimating a regression with just two data points and having no choice but to estimate a linear relationship, whereas if there were three data points, a curvilinear relationship may be a better fit to the data. Given the simplicity and ease of interpretation, we have chosen to bin our data by month. Note that if we organized our data another way, we would need to recalculate the running variable. For example, if we chose to have two-month bins instead of one-month bins, for a cutoff date of December 1, children born in October and November would have the same value of the running variable.

*5.3 Interpretation of the jump*

In **Figure 11**, for illustrative purposes we have chosen to focus on the kindergarten group and the first grade group. The jump, indicated in the brace where the running variable equals zero, is identified as the schooling effect. How should this schooling effect be interpreted? It seems that it is quantifying the effect of first grade schooling, but this is not entirely accurate. In Section 4.2, we discussed timing of assessment in the lab study and school study. Because children in the combined sample were assessed throughout the calendar year, this changes the interpretation of the jump in an important way. If all of the first grade children were assessed at the very end of the school year, the jump would be rightly interpreted as the effect of first grade – that is, the effect of one full year of first grade schooling. However, because these first grade children were assessed at random times throughout the school year, the interpretation of the jump is rather one full year of *kindergarten*. What all the children in the first grade group have in common is that they all have one full year of kindergarten under their belt, while the amount of first grade they have received is variable. Likewise, the group on the left were assessed at random times during the kindergarten year, so what they all have in common is some preschool or other childcare arrangement during the *previous* year.

## 6. Implementing a RD analysis
*6.1 rd command in Stata*

The following two conditions must be satisfied before a RD analysis can be conducted: (1) there is an arbitrary cut point that separates individuals into two groups, and if so, (2) the running variable (on the x-axis) is properly computed. If these are met, a RD can be conducted in Stata by installing a free command developed by Austin Nichols (Nichols, 2011) called **rd**. A full description and syntax of the command is provided in **Appendix 4**.

*6.2 Is age linear through the cut point?*

In RD, it is crucial that we have confidence that the jump we observe at the cut point is actually due to schooling and not to some other variable. One important check is to make sure that child age is continuous and linear through the cut point. That is, if we were to plot every child on a graph by age (where age is on the y-axis) and running variable (months from cutoff is on the x-axis), we should see a linear, positively sloping line. The plot for preschool and kindergarten children is shown in **Figure 12.1**. The figure shows that a plot of child age and "months from cutoff" yields a significant jump at the cut point ($p = .02$). The relation between these two variables should be perfectly linear, but the jump suggests otherwise. **Figure 12.2** shows the comparison between kindergarten and first grade children. Like the preschool vs. kindergarten comparison, there is also a statistically significant jump at the cut point ($p < .01$).
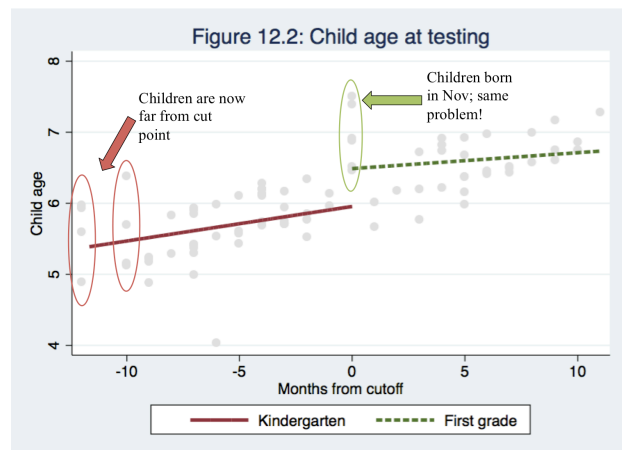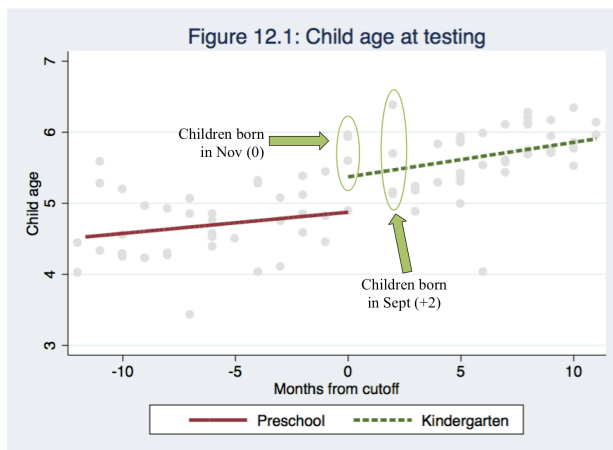


What might be causing this discontinuity? As shown in **Figure 12.1**, the kindergarten children who are immediately to the right of the cut point seem to be older than expected. Specifically, children with November and September birth months seem to be older than their peers who were

born in months further away from the cut point. This is also evident in **Figure 12.2**, where the first grade children born in November also seem to be unusually older than their peers.

As discussed in Section 4.4, we believe that parents of children who are born close to the cutoff entry date chose to wait an additional year before enrolling their children in kindergarten, commonly known as kindergarten redshirting. Parents may believe that their children are not yet emotionally or behaviorally ready for kindergarten, and opt to have their children enter kindergarten one year later. In what is known as a "donut hole RD," we can exclude the outliers near the cut point in order to improve the regression estimates (e.g., Barreca, Guldi, Lindo, & Waddell, 2011). However, as shown in **Figure 12.1**, if we exclude the kindergarten children born in November, note that we have zero kindergarten children born in the next month, October. As discussed in Section 4.3, having none or too few observations near the cut point preclude us from using a non-parametric model in which only the observations close to the cut point are used to estimate the jump. Even if we used a parametric model, this would bias our estimates of the jump. To make matters worse, children in the next month – September – also seem to be unusually older. Therefore, if we were use to use a donut hole approach, we would need to exclude observations from three months – September, October, and November – certainly not an ideal situation given our small sample size. It would be unclear as to how to interpret a jump with a three-month gap at the cut point. For these reasons, a preschool vs. kindergarten comparison would not be appropriate given the nature of our data.

However, for the kindergarten vs. first grade comparison as shown in **Figure 12.2**, we need only to address the problem of the first graders born in November who seem to be older than average; subsequent months do not seem to be particularly biased. One might still be concerned about the older kindergarten children, but because they are now further away from the cut point, these observations will have less of an impact on the estimation on the jump. Using a donut hole RD, we can exclude first grade children born in November, as well as exclude kindergarten children born in November (in order to keep each group as comparable as possible). If we do this, age is almost perfectly linear through the cut point ($p = .97$), as shown in **Figure 12.3**. Because of this, any jump that we observe in subsequent RD analyses can now be properly attributed to schooling rather than other variables. Therefore, we will focus only on the kindergarten vs. first grade

comparison in subsequent analyses, using a sample size of 49 kindergarten children and 36 first grade children across both lab and school studies.



Figure 12.3: Child age at testing
Children born in November excluded from both groups
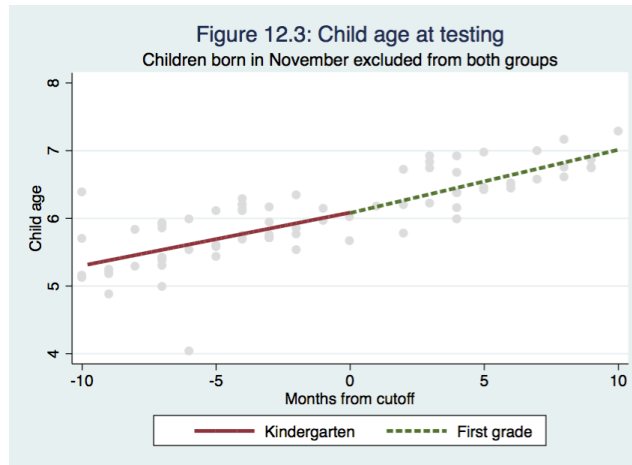
*6.3 Timing of assessment*

In a typical RD design, we would expect that the first graders would have better outcomes than kindergarteners because of a schooling effect. However, if first grade children were more likely to be assessed later in the school year compared to kindergarten children, RD may detect a significant schooling effect enjoyed by the first grade group when in actuality the effect was simply due to maturation. One way to counteract this problem is to ensure that children in each group are being assessed at the same time or at random times throughout the school year. Both options reduce the possibility that there will be significant differences in the timing of assessment across the groups that would lead us draw a spurious conclusion.

**Table 6** provides information on the number of kindergarten and first grade children assessed in each month in both the lab study and the school study. Recall that in the lab study, children were assessed throughout the calendar year; in the school study, children were assessed in the fall and spring, predominantly in the months of October, November, April, and May. Although there is not a universally-accepted method used to determine whether assessment times were sufficiently random, we can separate out children who were assessed during the first half of the school year (between September and December) from children who were assessed during the second half (January through June, as well as the summer months through August) in order to get a general

sense as to whether there are any significant differences in timing of assessments within grade level.

| Table 8: Number of children assessed in each month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Kindergarten** | | | | **First grade** | | | | **All** | | | |
| **Month** | L | S | All | Early/Late | L | S | All | Early/Late | L | S | All | Early/Late |
| Sep | 1 | 0 | 1 | | 1 | 0 | 1 | | 2 | 0 | 2 | |
| Oct | 0 | 11 | 11 | | 1 | 12 | 13 | | 1 | 23 | 24 | |
| Nov | 1 | 16 | 17 | 31 | 0 | 3 | 3 | 17 | 1 | 19 | 20 | 48 |
| Dec | 2 | 0 | 2 | | 0 | 0 | 0 | | 2 | 0 | 2 | |
| Jan | 0 | 0 | 0 | | 0 | 0 | 0 | | 0 | 0 | 0 | |
| Feb | 4 | 0 | 4 | | 0 | 0 | 0 | | 4 | 0 | 4 | |
| Mar | 1 | 0 | 1 | | 2 | 1 | 3 | | 3 | 1 | 4 | |
| Apr | 0 | 2 | 2 | | 0 | 4 | 4 | | 0 | 6 | 6 | |
| May | 1 | 8 | 9 | 18 | 2 | 4 | 6 | 19 | 3 | 12 | 15 | 37 |
| Jun | 1 | 0 | 1 | | 2 | 0 | 2 | | 3 | 0 | 3 | |
| Jul | 0 | 0 | 0 | | 2 | 0 | 2 | | 2 | 0 | 2 | |
| Aug | 1 | 0 | 1 | | 2 | 0 | 2 | | 3 | 0 | 3 | |
| Total | 12 | 37 | 49 | 49 | 12 | 24 | 36 | 36 | 24 | 61 | 85 | 85 |
| Note: L = Lab study, S = School study | | | | | | | | | | | | |

As **Table 8** shows, 31 out of 49 (63.3 percent) kindergarten children were assessed during the first half of the school year, while a lower proportion of first graders (17 out of 36 children, or 47.2 percent) was assessed during that same time period. Because children are expected to have lower outcomes at the beginning of the school year which then improve as children progress through school, our kindergarten vs. first grade comparison may *overstate* the jump because a larger proportion of kindergarten children were assessed earlier in the school year compared to first grade children.

## 7. Results

### 7.1 Early reading and math

The following Stata command was used:

```
rd reading mosfromcutoff if grade > -1 , z0(0)  graph mbw(500) kernel (rectangle)
```

rd is the Stata command for a regression discontinuity analysis. reading is the outcome variable; in this case, it is the child's letter-word identification W score. mosfromcutoff is the assignment

variable that holds the values of the running variable (months from cutoff). `if grade > -1` is an optional conditional statement that tells Stata to focus only on children who have a value of greater than -1 on the grade variable (where -1 = preschool, 0 = kindergarten, 1 = first grade). We are only focusing on the kindergarten vs. first grade comparison, so this statement excludes preschool children. `z0(0)` indicates that the discontinuity occurs when the value of the assignment variable equals 0. Finally, `graph mbw(500) kernel (rectangle)` tells Stata to fit a linear regression line for each group, as we do not have enough observations to estimate a local polynomial regression. In order to do this, the bandwidth must be set equal to or greater than 12, as there are 12 months on either side of the cut point. The number 500 tells Stata to set a bandwidth five times greater than the default bandwidth; 500 turns out to be a sufficiently large multiple to fit a linar regression line.

Graphical results of the RD for letter-word identification (early reading) are shown in **Figure 13.1**. There is a marginally significant jump at the cut point, suggesting that kindergarten schooling has a unique impact on early reading outcomes. However, as discussed in Section 6.3, this jump may be biased because a greater proportion of kindergarten children were assessed earlier in the school year compared to first grade children. Results for applied problems (early math) are shown in **Figure 13.2**; this jump is not significant. **Table 9.1** shows the regression estimates.
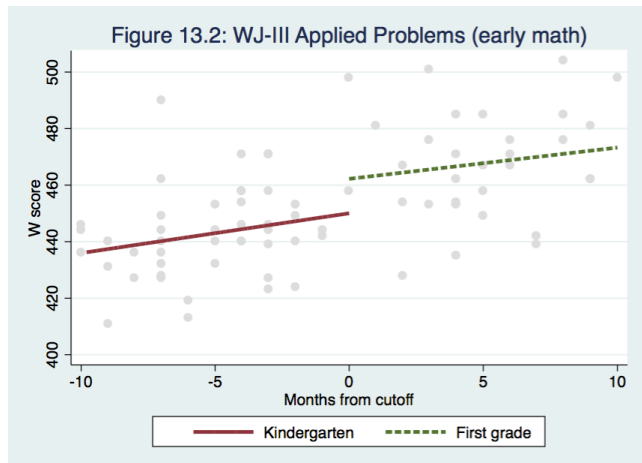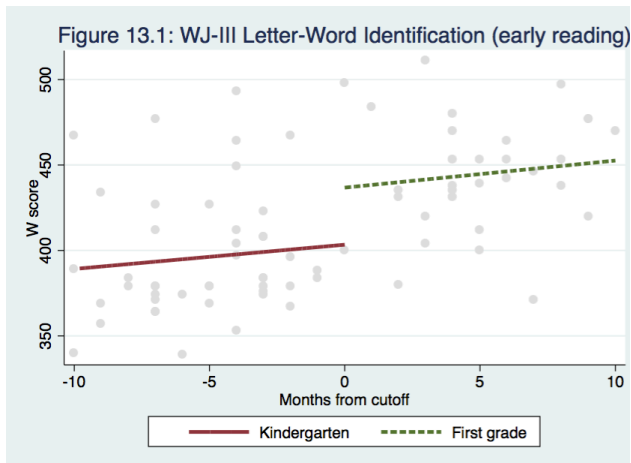


Figure 13.1: WJ-III Letter-Word Identification (early reading)

Figure 13.2: WJ-III Applied Problems (early math)

**Table 9.1:** Regression estimates for letter-word and applied problems

| VARIABLES | (1)<br>Letter-word | (2)<br>Applied problems |
|---|---|---|
| Effect of full year of kindergarten | 33.40+<br>(19.81) | 12.19<br>(9.503) |
| Observations | 75 | 75 |

Standard errors in parentheses; + $p<0.10$

The figures above seem to indicate that older children experience higher reading scores compared to younger children, as shown in the positive slopes for both linear regression lines. Are these slopes significantly different from zero? In order to calculate this, the following regression was conducted:

$$y = \beta_0 + \beta_1 madeormiss + \beta_2 mosfromcutoff + \beta_3 madeormiss \text{ X } mosfromcutoff + e$$

where *y* equals the letter-word W score, *madeormiss* is a dummy variable where kindergarten = 0 and first grade = 1, *mosfromcutoff* is the absolute value of the "months from cutoff" running variable, and an interaction term. The coefficient on the *mosfromcutoff* term tells us the slope of the linear regression line for kindergarten children (i.e., where *madeormiss* = 0). If *madeormiss* = 1, the coefficient on the interaction term tells us the slope of the linear regression line for first grade children. **Table 9.2** shows that the slopes for each group for both reading and math are not significantly different from zero.

**Table 9.2:** Regression estimates for slopes of the linear regression lines

| VARIABLES | (1)<br>Letter-word | (2)<br>Applied problems |
|---|---|---|
| madeormiss | 33.40+<br>(18.36) | 12.19<br>(8.863) |
| mosfromcutoff | -1.419<br>(2.133) | -1.406<br>(1.030) |
| madeormiss x<br> mosfromcutoff | 3.002<br>(3.220) | 2.511<br>(1.554) |
| Observations | 75 | 75 |
| R-squared | 0.325 | 0.363 |

Standard errors in parentheses; + $p<0.10$

*7.2 ERP behavioral measures*

We explored whether schooling had an effect on our ERP behavioral measures – accuracy and error rate on the Go/No-Go task – and children's reaction time. These variables were used as proxies for children's inhibitory control, a component process of EF. The graph for accuracy on Go (correct) trials is shown in **Figure 14.1**. There is no significant jump at the cut point. We also find a similar null finding for error rate on No-Go (incorrect) trials, as shown in **Figure 14.2**.



Figure 14.1: Accuracy on Go (correct) trials

Figure 14.2: Error rate on No-Go (incorrect) trials
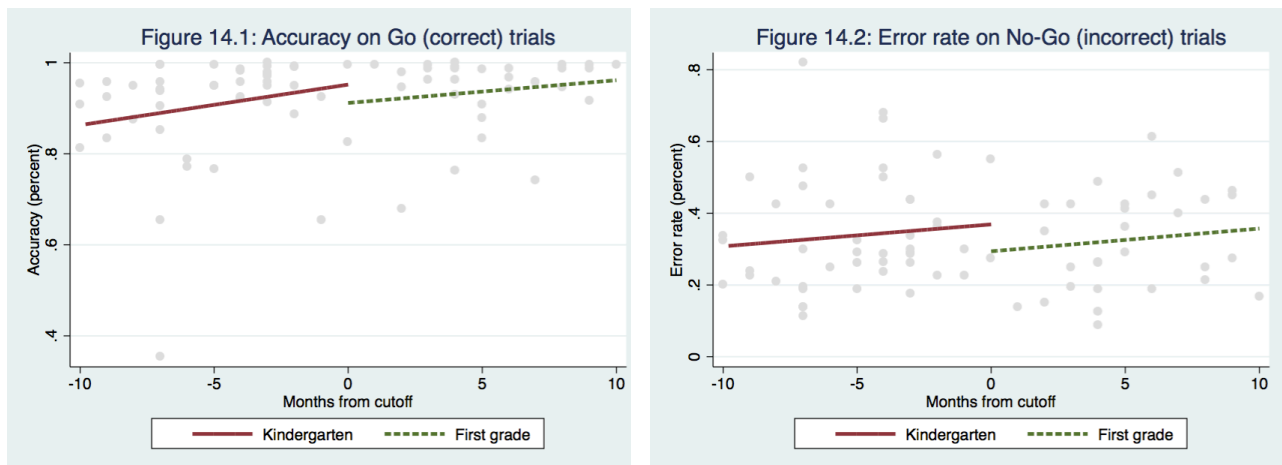
When looking at reaction times, there is no significant schooling effect on reaction times on Co (correct) trials as shown in **Figure 14.3**. Predictably, children respond faster on correct trials as they get older. When looking at reaction times on error trials, we find an interesting result. As shown in **Figure 14.4**, there is a marginally significant jump, such that a full year of kindergarten schooling is related to faster reaction times on error trials during the Go/No-Go task. When we look at boys and girls separately, we find that this effect is not present for boys, but the effect is significant for girls; these findings are presented in **Figures 14.5 and 14.6**. **Table 10** shows the regression estimates.

Figure 14.3: Reaction time on Go (correct) trials



Figure 14.4: Reaction time on No-Go (incorrect) trials



Figure 14.5: Reaction time on No-Go (incorrect) trials — Boys



Figure 14.6: Reaction time on No-Go (incorrect) trials — Girls
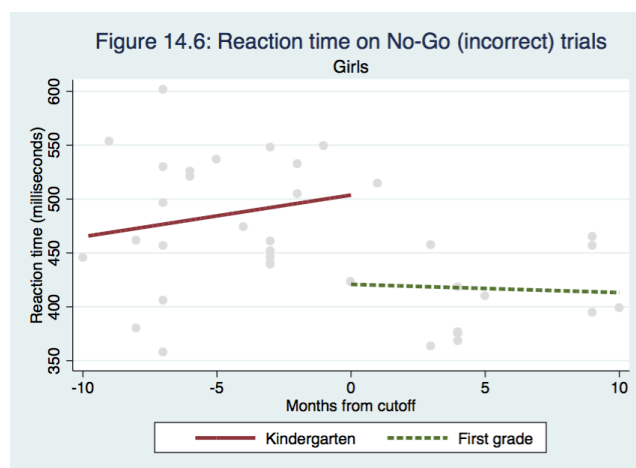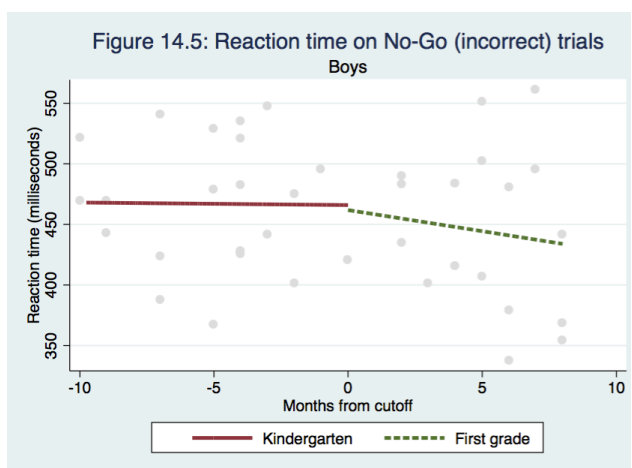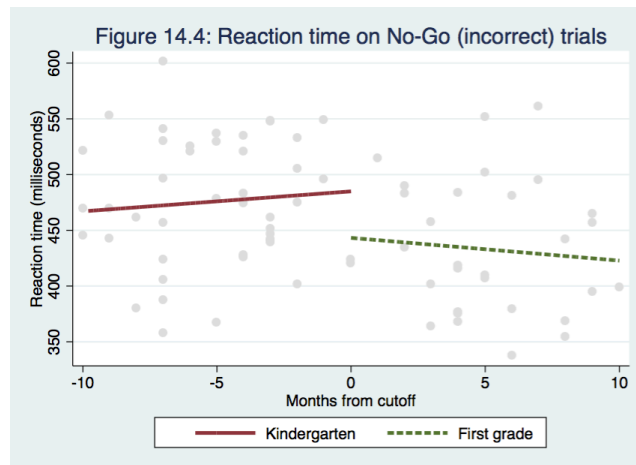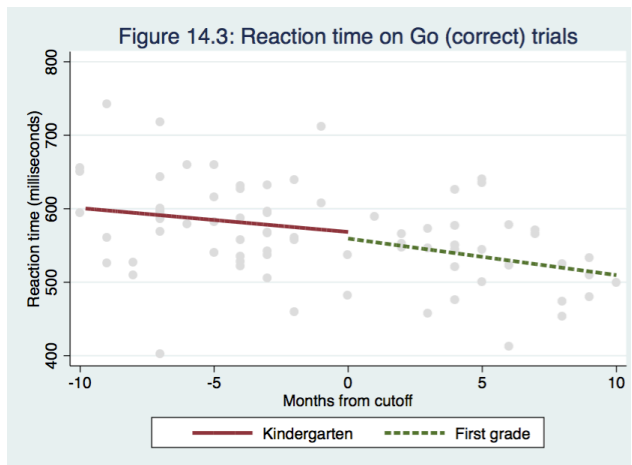
**Table 10:** Regression estimates for ERP behavioral variables

| VARIABLES | (1) Accuracy Go trials | (2) Error rate No-Go trials | (3) Reaction time Go trials | (4) Reaction time No-Go trials | (5) Reaction time (boys) No-Go trials | (6) Reaction time (girls) No-Go trials |
|---|---|---|---|---|---|---|
| Effect of full year of kindergarten | -0.040 (0.050) | -0.075 (0.071) | -8.973 (28.85) | -41.71+ (23.66) | -4.133 (33.69) | -82.85* (36.72) |
| | | | | | | |
| Observations | 75 | 75 | 75 | 75 | 39 | 36 |

Standard errors in parentheses; + $p<0.10$, * $p<0.05$

## 7.3 Error-related negativity (ERN)

Graphical results for the ERN at electrode sites Fz and FCz and ΔERN at Fz and FCz are shown in **Figures 15.1 through 15.4**. **Table 11** shows the regression estimates. ΔERN is a difference score that subtracts the brain activity on correct trials from the activity on error trials. As shown below, there is no effect of kindergarten on the magnitude of the ERN.



Figure 15.1: ERN at Fz

Figure 15.2: ERN at FCz

Figure 15.3: Delta ERN at Fz

Figure 15.4: Delta ERN at FCz
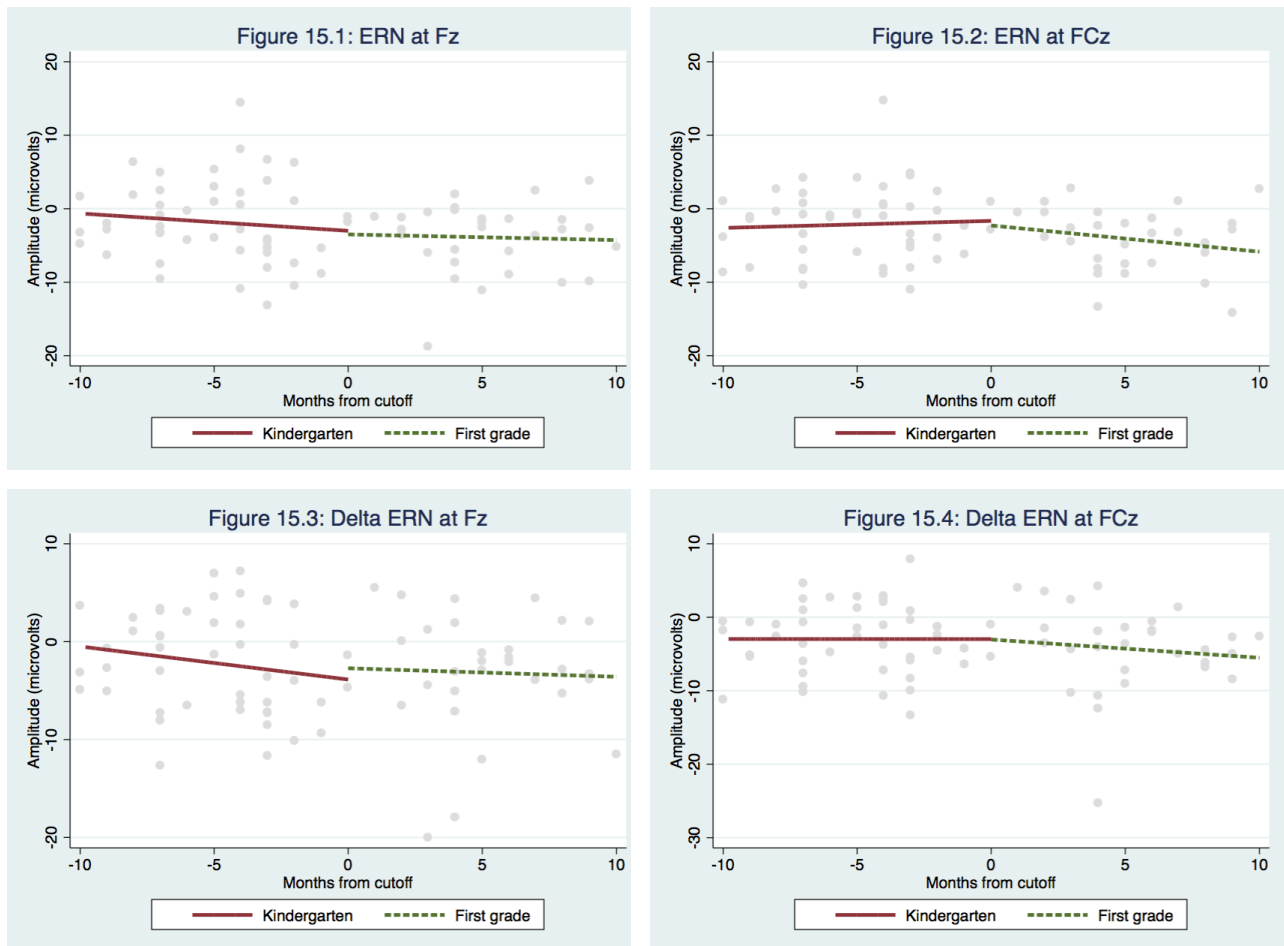
**Table 11:** Regression estimates for ERN and ΔERN

| VARIABLES | (1) ERN (Fz) | (2) ERN (FCz) | (3) ΔERN (Fz) | (4) ΔERN (FCz) |
|---|---|---|---|---|
| Effect of full year of kindergarten | -0.492 (2.655) | -0.626 (2.241) | 1.151 (2.946) | -0.057 (2.569) |
| Observations | 75 | 75 | 75 | 75 |

Note: Standard errors in parentheses

## 7.4 Error positivity (Pe)

Graphical results for the Pe at electrode sites CPz and Pz and ΔPe at CPz and Pz are shown in **Figures 16.1 through 16.4**. **Table 12** shows the regression estimates. ΔPe is a difference score that subtracts the brain activity on correct trials from the activity on error trials. Similar to our ERN results, there is no effect of kindergarten on the magnitude of the Pe. Like the ERN, adding gender as a covariate does not change the Pe results in a significant way.



Figure 16.1: Pe (on error trials) at CPz

Figure 16.2: Pe (on error trials) at Pz

Figure 16.3: Delta Pe at CPz

Figure 16.4: Delta Pe at Pz
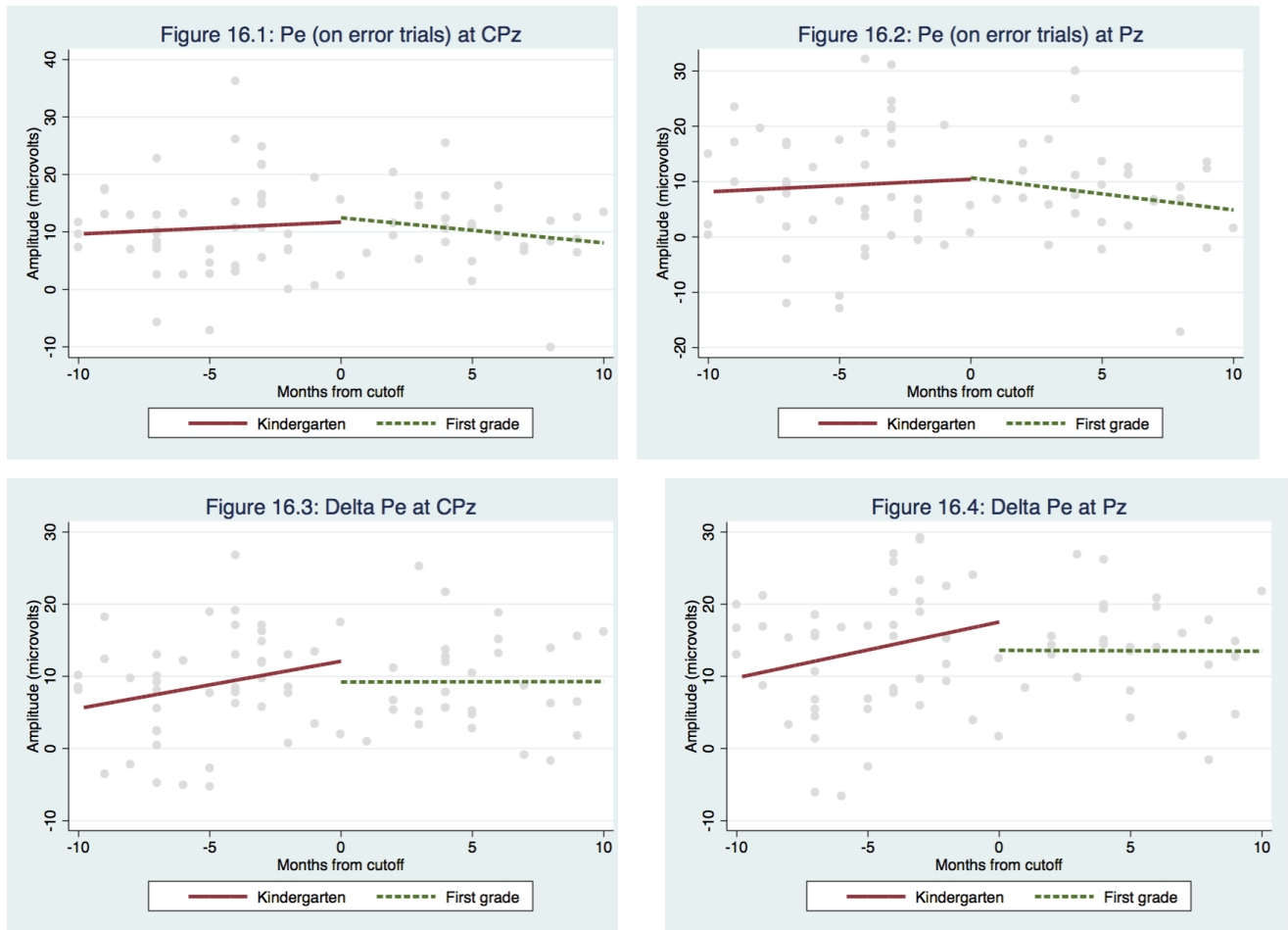
**Table 12:** Regression estimates for Pe and ΔPe

| VARIABLES | (1) Pe (CPz) | (2) Pe (Pz) | (3) ΔPe (CPz) | (4) ΔPe (Pz) |
|---|---|---|---|---|
| Effect of full year of kindergarten | 0.756 (3.759) | 0.275 (4.689) | -2.877 (3.466) | -3.918 (3.909) |
| Observations | 75 | 75 | 75 | 75 |

Note: Standard errors in parentheses

**8. Discussion**

*8.1 Schooling effects on early reading and math*

Previous research using the school cutoff technique has demonstrated that preschool and kindergarten schooling are related to word decoding ability (Burrage et al., 2008), and that children beginning their second year of preschool had stronger decoding and letter knowledge skills than same-age peers beginning their first year of preschool (Skibbe et al., 2011). Consistent with these studies, we also found that one full year of kindergarten schooling is related to stronger letter-word identification skills. However, we did not find a significant effect for early math skills. The two studies cited earlier did not include any math assessments, so a direct comparison between the studies cannot be done. Our null finding is not surprising, given research demonstrating that the amount of math instruction in kindergarten classrooms is minimal to none (Kim, Bell, & Morrison, 2011). However, because a greater proportion of our kindergarten children were assessed earlier in the school year compared to first grade children, our reading result may be biased and should be interpreted with caution.

*8.2 Schooling effects on ERP behavioral measures*

Findings of a schooling effect on self-regulation outcomes in young children have been inconsistent. Research has demonstrated a prekindergarten and kindergarten schooling effect for working memory and response inhibition (Burrage et al., 2008), but children's chronological age, rather than schooling, predicted children's self-regulation outcomes in another study (Skibbe et al., 2011). In our study, we used children's accuracy and reaction time on a speeded target discrimination task as standardized measures of inhibitory control. Better accuracy on Go trials and a lower error rate on No-Go trials, as well as how long it takes for children to respond, provide different windows to explore children's inhibitory control. We found no significant differences between the groups on accuracy and error rate on the Zoo Game.

We found null results for the reaction time on Go (correct) trials, but we did find a significant schooling effect for the reaction time on No-Go (error) trials, such that children who had a full year of kindergarten responded more quickly on error trials compared with those who did not have a full year of kindergarten schooling. Moreover, this effect was not found for boys but was present for girls. Quicker reaction times on both correct and incorrect trials are related to

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chronological age (e.g., Rueda et al., 2004), suggesting that biological maturation is associated with faster responses. This result was present despite the fact that there was no significant difference in average age between boys and girls, $t(84) = 1.04$, $p = .30$. Our gender finding contrasts with work suggesting that five- to seven-year-old girls are slower and more accurate compared to boys on a Go/No-Go task (Torpey, Hajcak, Kim, Kujawa, & Klein, 2011). However, research on adult populations demonstrates that women have faster reaction times on deviant targets compared to standard targets on a modified oddball task (Yuan, He, Qinglin, Chen, & Li, 2008).

*8.3 Schooling effects on the ERN and Pe*

Given theoretical and empirical links between the ERN and Pe and EF and motivation, we expected that schooling experiences would promote EF and motivation in young children, which would be observed in the ERN and Pe. Children with stronger EF skills should have larger (more negative) ERN amplitudes compared to children with weaker skills, as a larger ERN indicates that cognitive control is needed (e.g., Hajcak, 2012). Contrary to our expectations, our results suggest that early schooling has no discernable impact on the amplitude of the ERN. We also expected that schooling experiences, which often shape children's motivational beliefs and values, would be related to a larger Pe. Recent research has found that children's perceived competence and value beliefs are differentially related to the magnitude of the Pe (Kim et al., in preparation). Children engage in greater levels of social comparison in school and classroom settings, which may shape children's beliefs about achievement. As children are exposed to a growing number of academic subjects and with an increasing focus on assessment, children develop a set of beliefs about their academic competence as well as values and preferences for various activities and subjects. However, contrary to our predictions, we failed to find a schooling effect on the Pe.

## 9. Recommendations for future research

*9.1 Increase the sample size*

Based on this initial analysis, it is clear that a large sample size is imperative in order to be able to see effects. RD has a long tradition in economics and other social sciences with large data sets, but is still a relatively new method in psychology and education research. In particular, having

enough observations on either side of the cut point is very important, as the estimate of the jump is dependent on measuring outcomes for the youngest first grade children and the oldest kindergarten children. In this exploratory analysis, there were 49 kindergarten children and 36 first grade children who were included in the RD. Apart from a formal calculation of a minimum detectable effect size, researchers should aim to have at least double the sample sizes we report in this paper in order to better understand whether our null findings are truly null or due to a lack of precision.

### 9.2 Complement ERP measures with behavioral assessments

While behavioral measures of EF were implemented in both the lab study and the school study, data collection issues precluded us from incorporating these data in our current analysis. Because of the noise inherent in measuring the ERN and Pe in young children, it is important to complement ERP testing with behavioral assessments of EF and motivation. This would allow us to understand how behavioral measures of EF and motivation are related to electrophysiological processes thought to underlie these cognitive processes. A measure such as the Head-Toes-Knees-Shoulders task, with its good internal validity and ease of use with preschool children as well as with first grade children, can provide important information that the ERP technique cannot provide.

### 9.3 Assess children at multiple time points

There was substantial variability in children's ERN and Pe values compared to their early reading and math scores. It may be that children's electrophysiological processes are inherently variable across and within individuals, which would make it difficult to use these ERP components as stable measures of EF and motivation. Recent research with adult populations suggests that the ERN displays stable test-retest properties (Weinberg & Hajcak, 2011), which has important clinical implications. We might be able to use a child's ERN as a biomarker or endophenotype for clinical or developmental disorders, which may aid early detection and intervention. However, unpublished data drawn from the school study suggests that the ERN and Pe do not display within-subject stability from fall to spring assessment points in a normative sample. While the ERN may have adequate test-retest properties in adult populations, the ERN in younger children may not exhibit such stability. Future research should assess children at more

than two time points throughout the school year. By assessing children in multiple grades in the fall, winter, and spring, we can better understand whether the ERN and Pe changes – if at all – over the course of a school year, as well as the timing and magnitude of this change. Moreover, by collecting longitudinal data, we would be able to determine whether EF and motivation are more sensitive to general maturational factors rather than schooling experiences. A child's ERN and Pe value at a single time point, as used in the present study, may be too noisy to provide meaningful information about these ERP components.

*9.4 Standardize or randomize timing of assessment within and across groups*

Generally, we expect children to produce better outcomes later in the school year as a function of both learning and biological maturation. As discussed in Section 6.3, we found that a greater proportion of kindergarten children were assessed during the first half of the school year compared to first grade children. This might have biased our estimates of the jump and overstated the schooling effect we found for early reading outcomes. It was difficult to avoid this issue, as we combined samples from studies that had different data collection schedules. In future studies, children should be tested at random times throughout the school year, and researchers should be especially vigilant as to whether children in a particular grade are systematically being assessed earlier or later in the school year. Alternatively, children in all grades could be tested at roughly the same time during the school year, though this would introduce a number of logistical challenges.

*9.5 Consider the N2 and P3*

Because the ERN and Pe are generated by an individual's incorrect response to a stimulus, it is important for children to make a sufficient number of mistakes in order to have enough error trials that can be averaged together to produce a stable estimate of the ERN and Pe. For careful responders, these children may be excluded from the ERP analysis if they do not make enough mistakes. Yet, when considering cognitive processes such as EF and motivation, we want to include a wide range of children who vary in their accuracy and error rates as well as their speed of responding, as these may indicate meaningful differences in children's EF and motivation. It is common to have high attrition rates in child ERP studies of response-locked components such

as the ERN, because there is a non-trivial proportion of children who cannot be included in the analysis due to the child's low error rate on the experimental task.

Research on the electrophysiological correlates of EF and motivation have traditionally focused not on response-locked ERP components such as the ERN and Pe, but rather to stimulus-locked components such as the N2 and P3. For these components, the presentation of the stimulus, not the overt response to the stimulus, generates a distinct electrophysiological pattern. Just as the ERN is larger on incorrect trials than on correct trials, the N2 tends to be larger for an incongruent stimulus compared to a congruent one (e.g., Gehring et al., 1992). The conflict monitoring theory of the ERN would argue that this congruence effect reflects the same underlying component. Moreover, the scalp distribution and the time course of the ERN are very similar to those of the N2, providing further evidence that these two components might be closely related (Gehring et al., 2012). Turning to the Pe, evidence suggests that the Pe – particularly the late Pe commonly seen in adult populations – is a P300 to the erroneous response (Arbel & Donchin, 2009), and that the Pe and P300 both reflect processes involved in the processing of events that are motivationally significant (Ridderinkhof, Ramautar, & Wijnen, 2009).

Preschool children who succeeded on a behavioral EF assessment had smaller N2 amplitudes compared to children who failed (Espinet, Anderson, & Zelazo, 2013). Stronger EF skills were related to a smaller N2 but a larger P3b in a sample of seven- to nine-year-old children (Brydges, Fox, Reid, & Anderson, 2014). Turning to motivation, adults who held an entity view of intelligence (e.g., a belief that intelligence is due to innate factors or luck) had larger anterior frontal P3 amplitudes compared to individuals with an incremental view of intelligence (e.g., a belief that intelligence is due to effort and hard work; Mangels, Butterfield, Lamb, Good, & Dweck, 2006). Exploring both response-locked and stimulus-locked components from the same Go/No-Go task would yield important basic knowledge about how these components are related to each other in young children. This knowledge would help us to form more nuanced predictions about how response monitoring processes in the brain might be related to children's EF and motivation.

*9.6 Collect information on school- and classroom-level characteristics*

While schooling may influence children's development of EF skills and motivational beliefs and values, there may have been large variability in the type and amount of instruction that children received in their preschool and early elementary classrooms. Children in our combined sample attended many different schools, and these schools may have placed differing levels of emphases on promoting behavioral skills related to EF. The strongest effects linking schooling to EF have come from studies that have assessed the efficacy of evidence-based programs specially designed to promote these skills, as well as computerized training programs (Diamond, 2012). In future studies, data should be collected from teachers and school staff on pedagogical strategies as well as the amount and type of instruction present in classrooms. This would allow us to determine the specific characteristics of the school and classroom environment that shape EF and motivation.

## 10. Conclusion

This study used an analysis technique called regression discontinuity to explore schooling effects on the magnitude of the ERN and Pe, given theoretical links between these two error-related ERP components and EF and motivation. While we found some evidence of a kindergarten schooling effect on children's reading skills and inhibitory control, we did not find evidence that schooling uniquely predicts variability in the ERN and Pe. The use of RD in ERP research has the potential to yield important insights into how school and classroom experiences can shape development through changes at the neurophysiological level.

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**Chapter IV**
**General discussion**

The two empirical papers presented above demonstrate that behavioral, neurological, and educational perspectives can be successfully integrated in the study of early cognitive processes. In this concluding chapter, I briefly discuss three take-home messages that will point to areas of future research.

**Motivation and the Pe: There's something really here!**

The results presented in Chapter II suggest that individual differences in children's ability and value beliefs, as well as achievement-related emotions, are related to the Pe but not to the ERN. This replicates work demonstrating that ability mindsets, conceptually similar to achievement goal orientations, are related to the magnitude of the Pe in adult populations (Moser, Schroder, Heeter, Moran, & Lee, 2011) as well as in children using the Go/No-Go Zoo Game (Fisher, Schroder, Danovitch, & Moser, 2015), with no associations with the ERN. Concern over mistakes is also related to the Pe in adults but not to the ERN (Tops, Koole, & Wijers, 2013). As a whole, these studies provide converging evidence from different theoretical perspectives and populations that the Pe, and not the ERN, may reflect individual differences in motivation. Notably, these findings also suggest that the relation between motivation and the Pe may be due to some fundamental motivational process that is shared in common across different conceptualizations of motivation. The fact that a consistent story is emerging for the importance of motivation in understanding the error positivity may lead to breakthroughs in our understanding of both early motivational processes as well as the neurophysiology of response monitoring.

**What does the Pe really represent?**

Despite this converging body of evidence linking the Pe and motivation, important questions remain regarding the functional significance of the Pe. The Pe has been thought to reflect the

conscious awareness of and the increased attention devoted to a mistake, as well as the emotional response to the mistake (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). The results presented in Chapter II and other published studies suggest that the Pe may also be characterized as indexing trait-like motivational processes related to response monitoring, which include beliefs, values, and emotions related to achievement.

What then does the Pe then really represent? Does it reflect the conscious awareness of the mistake, or does it also reflect individual differences in motivation? Does the Pe reflect a specific achievement-related emotional response to the mistake that should be understood in terms of motivational processes? Given research suggesting that the Pe is sensitive to age (Grammer, Carrasco, Gehring, & Morrison, 2014), does the Pe index maturational factors during the school transition period? Is the Pe related to all of these processes, or does it represent some underlying fundamental process that we have not yet assessed or something else entirely? It is clear that there is much to be learned about the nature of these error-monitoring processes in early childhood, and what the Pe might represent.

**Schooling and neuroscience: Still "a bridge too far"?**

John Bruer, in his 1997 article "Education and the brain: A bridge too far," argues that neuroscience has little application to teachers and classroom practice. More recently, others have countered that while scientific and pragmatic challenges still remain, education and neuroscience approaches can potentially be integrated in a way that can promote both neuroscientific research and classroom practice (Varma, McCandliss, & Schwartz, 2008). I argue that the question regarding the bridge between education and neuroscience is not one of length, but rather of construction. The "length" analogy suggests that these two fields are so far apart in terms of assumptions, modes of thinking, theoretical perspectives and methodologies, and questions of interest, that education and neuroscience can never be bridged successfully. Rather, I propose that these two fields can be integrated successfully if the bridge is constructed more thoughtfully and creatively.

There does not always need to be a clear application to classroom and teacher practice in order

for neuroscience research to be beneficial for education. In Chapter II of this dissertation, findings were presented showing that individual differences in motivation are related to an ERP component called the error positivity. Understanding the neural correlates of processes that are important for learning and achievement, such as motivation, can itself be a way to bridge neuroscience and cognitive processes that are educationally relevant. In Chapter III, a quasi-experimental research design called regression discontinuity was used to explore whether schooling had unique effects on electrophysiological phenomena associated with EF and motivation. While we did not find any evidence of schooling effects, the study does generate other research ideas that might represent a sturdier bridge construction between education and neuroscience. For example, the study did not examine specific aspects of schooling or classroom practice, although it is likely that certain aspects of the classroom experience might be more strongly related to motivation and EF compared to other aspects. It may also be the case that the ERN and Pe are not stable indicators of EF and motivation, respectively, in young children, which may explain the null findings. Building a larger knowledge base about how early schooling influences the development of motivation and EF may allow us to build a stronger bridge that will eventually put us in a more effective position to explore schooling effects on brain measures of these processes.

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**Appendix 1**
**Achievement goal orientation protocol**

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**PSYCHOLOGY**
*exploring the mind*

**Achievement motivation: Wedgits puzzle**
*A brain-behavior study of children's errors, motivation, and executive functioning:*
*An integrative approach*

**Materials needed:**
- Wedgits
- Camera
- Stopwatch

Researcher instructions:
1. Make sure the camera is pointed at the child and recording; make sure that you will not block the camera when you sit down.
2. Show the child the blocks and the design on the first card (blue square 8). Say, **"First, I want you to make the blocks look exactly like the blocks in this picture. Can you make the blocks look like this picture?"**
3. Let the child work until he/she is finished. You can help him/her if he/she does not understand how to make the blocks look like the card.
4. Now show the child the design on the second card (blue square 3). Say, **"You did a great job with that! Now, I want you to make the blocks look exactly like this picture."**
5. Let the child work without helping him/her. Stop the child at 4:00 if he/she is still working.

6. If the child finishes puzzle 2 in the allotted time, (most children), **SKIP TO STEP 7.**
   If the child does **not** finish puzzle 2 in the allotted time, **SKIP TO STEP 9.**

7. Now show the child the design on the third card (red circle 14). Say, **"You did a great job with that one, too! Let's do another one. Make the blocks look exactly like this picture."**
8. Let the child work without helping him/her. Stop the child at 4:00 if he/she is still working.

9. Tell the child, **"We are out of time. If you had more time to work, would you like to keep trying this one (hold up the picture of the last completed puzzle) or build this other one again (hold up the last picture)? Record child response. "Why?"** Record child response.
10. Ask the child, **"How hard was the last puzzle?** *(Point to it)* **Was it easy, a little hard, or very hard?"**

| Puzzle #1 (Easy) | |
|---|---|
| Completed? | |
| Time to completion | |
| Time on task | |
| **Puzzle #2 (Medium)** | |
| Completed? | |
| Time to completion | |
| Time on task | |
| **Puzzle #3 (Hard; if necessary)** | |
| Completed? | |
| Time to completion | |
| Time on task | |

9a. Which puzzle did the child want to keep trying?

☐ the easier, completed puzzle
☐ the harder, incomplete puzzle

9b. Why did the child want to try that one again?

_____

_____

10. How hard did the child think the last puzzle was?   ☐ Easy   ☐ A little hard   ☐ Very hard

**Appendix 2**
**Puppet interview protocol**

**Puppet Interview Protocol**

1. Show child the five different puppets of his/her gender and say, **"These puppets are children just like you and they are going to talk about different things that happen in school. Which one is the most like you?"** Have child pick the one that is the most like him/her. Say, **"Oh, this is Ana/Andrew!"**

2. Produce the matching puppet and say, **"Here is another child just like you and Ana/Andrew. S/he is a friend of Ana/Andrew and her/his name is Beth/Bobby!"**

3. Say, **"Ana/Andrew and Beth/Bobby go to the same school and they have the same teacher. They have a teacher just like yours. They will talk about themselves and what they like. They like different things but that's OK because they are different kids. It's OK for kids to feel differently."**

4. Give the children two practice items. Have Ana/Andrew say, **"I like pizza"** and Beth/Bobby say, **"I don't like pizza."** Ask, **"Which puppet thinks the same as you?"**

5. Then have Beth/Bobby say, **"I like recess in school"** and have Ana/Andrew say, **"I don't like recess in school."** Ask, **"Which puppet thinks the same as you?"**

6. Administer the items on the sheet, varying which puppet speaks first. Record the child's answer, either marking the sentence or a + or − (you can fill the other column in afterward).

**Achievement motivation: Puppet interview**
*A brain-behavior study of children's errors, motivation, and executive functioning:*
*An integrative approach*

"Ana/Andrew and Beth/Bobby are going to talk to you about puzzles like the ones you just did."

| | Statement | Positive (+) or negative (-)? | |
|---|---|---|---|
| ____ | I like doing puzzles like this one | | |
| ____ | I don't like doing puzzles like this one | + | - |
| ____ | I don't have fun doing puzzles | | |
| ____ | I have fun doing puzzles | + | - |
| ____ | I want to know more about puzzles | | |
| ____ | I don't want to know more about puzzles | + | - |
| ____ | I feel happy when I am doing puzzles | | |
| ____ | I don't feel happy when I am doing puzzles | + | - |
| ____ | Puzzles like this one are hard | | |
| ____ | Puzzles like this one are easy | + | - |
| ____ | I know how to do puzzles | | |
| ____ | I don't know how to do puzzles | + | - |
| ____ | I can't do puzzles | | |
| ____ | I can do puzzles | + | - |
| ____ | I'm good at puzzles | | |
| ____ | I'm not so good at puzzles | + | - |

**Appendix 3**
**Questions in the CBQ anger/frustration subscale**

2.      Gets angry when told s/he has to go to bed.
14.     Has temper tantrums when s/he doesn't get what s/he wants.
30.     Gets quite frustrated when prevented from doing something s/he wants to do.
40.     Gets angry when s/he can't find something s/he wants to play with.
61R.    Rarely gets upset when told s/he has to go to bed.
87.     Gets angry when called in from play before s/he is ready to quit.

# Appendix 4
## Stata documentation on the Regression Discontinuity (rd) estimator

**rd** implements a set of regression-discontinuity estimation methods that are thought to have very good internal validity, for estimating the causal effect of some explanatory variable (called the treatment variable) for a particular subpopulation, under some often plausible assumptions.  In this sense, it is much like an experimental design, except that levels of the treatment variable are not assigned randomly by the researcher.  Instead, there is a jump in the conditional mean of the treatment variable at a known cutoff in another variable, called the assignment variable, which is perfectly observed, and this allows us to estimate the effect of treatment as if it were randomly assigned in the neighborhood of the known cutoff.

**rd** is an alternative to various regression techniques that purport to allow causal inference (e.g. panel methods such as xtreg), instrumental variables (IV) and other IV-type methods (see the ivreg2 help file and references therein), and matching estimators (see the psmatch2 and nnmatch help files and references therein).  The rd approach is in fact an IV model with one exogenous variable excluded from the regression (excluded instrument), an indicator for the assignment variable above the cutoff, and one endogenous regressor (the treatment variable).

**rd** estimates local linear or kernel regression models on both sides of the cutoff, using a triangle kernel.  Estimates are sensitive to the choice of bandwidth, so by default several estimates are constructed using different bandwidths. In practice, **rd** uses kernel-weighted suest (or ivreg if suest fails) to estimate the local linear regressions and reports analytic SE based on the regressions.

In the simplest case, assignment to treatment depends on a variable Z being above a cutoff Z0.  Frequently, Z is defined so that Z0=0. In this case, treatment is 1 for Z>=0 and 0 for Z<0, and we estimate local linear regressions on both sides of the cutoff to obtain estimates of the outcome at Z=0.  The difference between the two estimates (for the samples where Z>=0 and where Z<0) is the estimated effect of treatment.

There should be two or three variables specified after the **rd** command; if two are specified, a sharp RD design is assumed, where the treatment variable jumps from zero to one at the cutoff.  If no variables are specified after the **rd** command, the estimates table is displayed.

> **rd** outcomevar [treatmentvar] assignmentvar [if] [in] [weight] [, options]