ABSTRACT

Title of dissertation: THE RESPONSE-MONITORING MECHANISM: INFLUENCE OF FEEDBACK AND TEMPERAMENT

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The purpose of the current study was to examine behavioral and physiological processes underlying response-monitoring and to document the manner in which these processes are expressed during early childhood. As well, this study examined two factors important in understanding individual differences in monitoring: performance feedback and temperament. A total of seventy-four children (mean age 7.5 years) were tested using a modified flanker paradigm administered in both no-feedback and feedback conditions. Accuracy and reaction time measures of behavioral performance were assessed as well as event-related potentials linked to response execution and feedback presentation. Data were also examined in relation to the temperamental dimensions of shyness and inhibitory control.

The results indicate a strong impact of trial-by-trial feedback on both behavioral and physiological measures. Overall, feedback served to increase children's task engagement as evidenced by fewer errors of omission and faster reaction times. Similarly, the physiological measures also varied as a function of feedback such that the error-related Positivity (Pe) and the feedback-related negativity (FRN) were more pronounced on incorrect as compared to correct trials in the feedback condition. Larger FRN responses were also associated with fewer errors of commission. These findings were further moderated by individual differences in temperament. Specifically, feedback was particularly influential in increasing task involvement for children low in inhibitory control and enhancing performance accuracy for children low in shyness

Overall these results confirm a strong impact of feedback on task engagement as assessed by children's behavioral performance and physiological reactivity. Findings are presented in the framework of individual differences in cognitive control and variations in children's physiological measures of response-monitoring are discussed. Several avenues for future research are provided which emphasize the need for investigations of response-monitoring in young children and also highlight the importance of exploring the applicability of these assessments across various cognitive and social contexts.

THE RESPONSE-MONITORING MECHANISM:

INFLUENCE OF FEEDBACK AND TEMPERAMENT

by
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CHAPTER I: GENERAL OVERVIEW

The term ‘self-regulation’ broadly describes a multitude of processes involved in the implementation of control over one’s own actions. This concept encapsulates the notion of regulation *of* the self *by* the self and as such, the understanding of self-regulation has been postulated to provide key insights into how the ‘self’ is composed (Vohs & Baumeister, 2004). Recent efforts to identify the neural mechanisms underlying the development of self-regulation have lead to an increase of studies with a focus on children’s attention processes. Within the neuroscience framework, these attention processes are commonly referred to as ‘cognitive control’. Although a number of different terms are used to describe cognitive control, this concept is ultimately defined by the inclusion of processes that require voluntary control over attention resources and the exclusion of automated attention processes (Casey, Tottenham, & Fossella, 2002).

The development of cognitive control corresponds to several major maturational changes in brain activity including: 1) a posterior to anterior shift in neural activation, 2) a more localized, less diffuse pattern of activation within regions, and 3) specialized recruitment of regions during cognitive control tasks (Bunge & Wright, 2007; Casey, Tottentham, Liston, & Durston, 2005). These neural changes are associated with specific cognitive control skills such as selective attention, working memory, and interference suppression which underlie a number of behavioral phenomena that characterize specific examples of self-regulated behavior such as impulse control and delay of gratification. Thus, a number of cognitive control skills contribute to self-regulation, however, the ability to consistently engage in self-regulatory behaviors across a variety of contexts may be more closely linked to the specific skill of response-monitoring (see Figure 1).

Response-monitoring is a component of cognitive control that can occur in conjunction with other task specific cognitive control skills. The process of response-monitoring is directly related to the detection and evaluation of responses/behaviors and is further responsible for initiating appropriate strategy adjustments. As such, response-monitoring is hypothesized to play a particularly important role as a mechanism which aids in the transition between task specific cognitive control and the emergence of a broader ability to flexibility engage self-regulated behavior across multiple situations.

Although many behavioral measures provide indirect assessments of response-monitoring, these measures do not fully capture the detection, evaluation, and adjustment segments involved in the complete response-monitoring process. Furthermore, behavioral approaches also fail to classify the neural systems involved in the activation of this regulatory mechanism. Knowledge of the biological underpinnings of response-monitoring could significantly contribute to the understanding of plasticity within regulatory systems throughout development. Current research on response-monitoring in adults has made considerable strides in documenting this capability at both behavioral and physiological levels (Gehring, Himle, & Nisenson, 2000; Luu, Collins, & Tucker, 2000; Miltner, Braun, & Coles, 1997; Pailing, Segalowitz, Dywan, & Davies, 2002; Van Veen & Carter, 2002). However, in children, behavioral markers and maturation patterns of the neural systems involved in response-monitoring are less clearly understood.

One reason for the slow progression in neuro-developmental research in children is the limited nature and number of integrative methodological approaches used in developmental studies. Constraints on the type of physiological measures used in children have translated to a very restricted understanding of the precise relations between physiological and behavioral indices of cognitive skills such as response monitoring. Fortunately, strides in adapting a variety of methodologies to suit developmental studies (i.e. functional magnetic resonance imaging; fMRI) as well as an increased understanding of specific neural components related to the development of cognitive control (e.g. the N200, see Lamm, Zelazo & Lewis, 2006) are providing new opportunities to examine and interpret the neural circuitry of behavioral functions in children. In addition, a growing number of studies focusing specifically on the behavioral and physiological correlates of response-monitoring in children are also beginning to emerge (e.g. Burgio-Murphy et al., 2007; Davies, Segalowitz, & Gavin, 2004; Henderson, 2003).

In addition to identifying the neural underpinnings of response-monitoring, examination of external and internal factors that affect the emergence and refinement of this cognitive control mechanism are also under investigation. For the purposes of the current study, external factors are defined as cues that are generated by others or the environment. In contrast, internal factors are defined as signals originating from the self irrespective of input from other people or the environment. One particularly influential external factor in cognitive development is performance feedback. Throughout development children become more capable of utilizing a variety of forms of feedback (i.e. verbal and visual) to initiate self-reflection, alter behavior patterns, and guide future actions. Even though children can regulate themselves via the use of feedback, significant changes in the consistency and efficiency of children's self-regulation are hypothesized to occur when externally initiated evaluation processes (i.e. feedback) become more internalized in the form of response-monitoring. However, it is currently unclear as to what point in the response-monitoring process external feedback is first used and when feedback shifts from exerting temporary to more permanent influence on the response-monitoring process.

Interestingly, the manner in which external feedback is interpreted and incorporated into the response-monitoring process may vary in accordance with internal differences within the child known as temperament. Broadly, temperament is thought to reflect stable predispositions towards emotional reactivity which guide behavioral regulation and adaptation patterns (Fox & Henderson, 1999). Although a great deal of research has been conducted linking temperament traits to general self-regulation outcomes, relatively little is known regarding the association between temperament and the development of physiological indices of the response-monitoring mechanism.

Overall, the investigation of the neural systems underlying the development of response-monitoring is important because this cognitive control component is essential to the implementation of successful self-regulation as defined by behavioral adaptation and favorable socio-emotional outcomes. Therefore, the purpose of the current investigation was to examine the relation between a specific set of physiological and behavioral markers of response-monitoring as assessed via a selective attention paradigm and to document the manner in which these markers are expressed in young children. Specifically, response-monitoring markers were examined in two contexts: 1) in task conditions with and without performance feedback, and 2) from the perspective of individual differences in children’s temperament traits.

CHAPTER II: LITERATURE REVIEW

The response-monitoring process

Response-monitoring is the higher order integrative skill of monitoring ones own actions and subsequently modifying future behavior. Developmentally, the activation and maturation of this mechanism can be viewed as a critical driving force behind advancements in self-regulated behavior (Davis, Bruce, Synder, & Nelson, 2003; Luu, Flaisch, & Tucker, 2000). According to Scheffers and colleagues (Scheffers, Coles, Berstein, Gehring, & Donchin, 1996) the monitoring process involves at least two distinct facets, the detection of an error and the means to take correct action or compensatory behavior in response to the error.

Although various terminologies have been used to describe the response-monitoring process, the majority of self-regulation theories commonly emphasize response monitoring as the key process through which flexible and efficient response adaptation to situational specific demands are accomplished. For example, according to Norman and Shallice's (1986) developmental model of self-regulation, the general 'supervisory system' that controls responses to environmental contingencies also needs to have a monitoring process in place to ensure the proper functioning and performance of the larger control system. In this view, response-monitoring has been defined as "…the first stage in multistage models of self-regulation (e.g. Bandura, 1986; Kanfer & Karoly, 1972; Kanfer & Hagerman, 1981)", and it has further been characterized as a signal that creates "a temporary disengagement from automaticity, or a transition from mindlessness to mindfulness" (Karoly, 1993, pp. 33).

Likewise, Kopp (1982; 1991) also proposed a model of self-regulation in which children develop the means to form clear representations of external expectations (i.e. caregiver expectations) and to act in accordance with these expectations. In this model, Kopp emphasized the achievement of self-controlled behavior, or the ability to inhibit behavior, as a hallmark of self-regulation. The mechanism through which a child achieves self-control is highlighted as a response-monitoring process which Kopp terms the self-monitoring system. This system entails internalized recall of external expectations and balances these peripheral expectations with one's own personal expectations and goals. Integrating these components allows the child to apply behavioral self-control, or inhibitory control, in appropriate contexts and thus accomplish self-regulation.

Across the various models, it is generally agreed that the process of response-monitoring as a whole serves several functions. First, monitoring of accurate or appropriate performance provides factual information regarding the task at hand and task relevant goals. Second, monitoring of performance outcomes can influence motivation levels. Third, monitoring also triggers self-reflection (Bandura, 1986; Karoly, 1993). These functions allow for the detection of errors and the initiation of remedial action to compensate for those errors when necessary (Scheffers & Coles, 2000). Yet evidence suggests that the manner and degree to which these functions are utilized on a consistent basis may contribute to variability in self-regulation patterns.

Understanding the normative development of self-regulation is a critical step in understanding the etiology of various psychological outcomes typically plagued by self-regulation deficits (Calkins & Fox, 2002; Posner & Rothbart, 2000). Defining the mechanisms that support the links between self-regulation and maladaptive disorders will contribute to diagnostic and intervention advancements. However, previous studies of self-regulation outcomes have focused on general regulation behaviors, such as compliance and delay of gratification (e.g. Kochanska, Coy, & Murray, 2001; Metcalfe & Mischel, 1999; Mischel, Shoda, Rodriguez, 1989), as opposed to the underlying mechanism of response-monitoring. Generally, developmental disorders associated with poor self-regulation in the form of externalizing behaviors (i.e., aggression; AD/HD; ODD) appear to have problematic activation, and or maintenance of, response-monitoring whereas disorders associated with internalizing behaviors (i.e. obsessive-compulsive disorder; OCD) seem more vulnerable to the over-activation of the response-monitoring mechanism (Gehring et al., 2000).

Although a great deal of research has focused on self-regulation difficulties and related maladaptive outcomes, studies have also been conducted to investigate positive outcomes associated with self-regulation. Early self-regulatory behaviors are predictive of a variety of adaptive outcomes (McCabe, Cunnington, & Brooks-Gunn, 2004) including social competence (Denham et al., 2003), emotional knowledge (Schultz, Izard, Ackerman, & Youngstrom, 2001), resiliency (Eisenberg, et al., 1997), and cognitive achievements in later childhood (Shoda, Mischel, & Peake, 1990). Interestingly, the resilience literature indicates that resilient youths are more likely to display enhanced self-regulation as compared to non-resilient youths, particularly if the child has experienced active monitoring by an adult authority figure (Buckner, Mezzacappa, & Beardslee, 2003). Findings such as this fit well with the developmental theories of self-regulation in which the response-monitoring mechanism shifts from external to internal monitoring. As this transition occurs, children are better able to self-engage their response-monitoring mechanism and thus display regulated behaviors across a variety of optimal and sub-optimal contexts.

Development and assessment of response-monitoring

The development of general cognitive control, which subsumes the response-monitoring mechanism, has been associated with maturation of the frontal lobe region. In particular, prefrontal cortex (PFC) activity has long been noted as a major contributor to a child's increased ability to adapt to regulatory demands (Benes, 2001; Bjorklund & Harnishfeger, 1995; Casey, Giedd, & Thomas, 2000; Diamond, Kirkham, & Amso, 2002). Implicated in a variety of cognitive functions, developmental changes have been noted to occur in this region from birth through adolescence (Fuster, 2002; Giedd, 2004). These changes result in more efficient inter-regional neural processing and are associated with dramatic increases in self-regulatory ability across early childhood (Casey, 2002). Distinct PFC regions have been linked to specific aspects of regulatory control. For example, the anterior cingulate cortex, lying in the medial frontal lobe, is thought to register the concordance between current goals and actions (ACC; Bush, Luu, & Posner, 2000). Such ACC-related functions are thought to facilitate action monitoring, goal-directed behavior, conflict detection, mediation of response selection, and modulation of attention (Bush et al., 2000; Davies et al., 2004; Rothbart, Sheese, & Posner, 2007; van Veen & Carter, 2002).

The ACC has further been delineated in terms of dorsal and rostral-ventral subdivisions, which are linked to cognitive versus affective processing functions, respectively. The cognitive subdivision has a number of reciprocal connections with the lateral PFC, parietal cortex, and motor areas while the affective division is coupled with a number of limbic structures including the amygdala, the nucleus accumbens, the hypothalamus, and the hippocampus as well as the orbital frontal region (see Bush et al., 2000 for a review). Due to these diverse connections the ACC has been characterized as a 'transitional cortex' that integrates cognitive, motor and motivational functions (Devinsky & Luciano, 1993; Devinsky, Morrell & Vogt, 1995; Ladouceur, Dahl, & Carter, 2007; Vogt & Pandya, 1987).

A primary cognitive function of the ACC is the detection and correction of inaccurate responding. Current theories further suggest that in addition to response detection, the ACC also servers to filter as well as propagate signals from the mesocenphalic dopamine system that are indicative of subject performance. Recent evidence from the primate literature suggests that beyond the basic function of indicating response performance (i.e. signaling error detection) the ACC may also be involved in tracking outcomes of response performance. Specifically, the ACC appears to be involved in learning the value of response-choice actions as they relate to reward and non-reward outcomes (Kennerley, Walton, Behrens, Buckley, & Rushworth, 2006).

Affective aspects of ACC functioning include processing distress and awareness of emotion states (Posner & Rothbart, 2000). For example, subjects who were shown highly emotional film clips during a PET scan demonstrated differences in ACC blood flow that were positively correlated to their individual level of emotional awareness (Lane, Reiman, & Axelrod, 1998). The ACC has also been associated with directing attention and motivation (Davis, Bruce, and Gunnar, 2002; Posner & Dehaene, 1994).

Moreover, Rothbart and colleagues (Posner & Rothbart, 2000; Rueda, Posner, & Rothbart, 2004) hypothesize that individual variability in ACC engagement within an executive attention network may underlie differences in self-regulation processes as assessed via temperamental differences in negative affect and effortful control.

Despite interest in the ACC and its associated cognitive-affective processing functions, little research has directly studied the maturation of this neural region in young children. Research conducted with older children and adolescents suggests that in addition to the relatively late maturation period of the PFC, the ACC also continues to mature throughout childhood into early adulthood. Imaging data indicate increased activation of the ACC across development (Adleman et al., 2002) which may be linked to more powerful or more synchronous firing of the neurons within the ACC. Alternatively, ACC activation may also increase due to enhanced connections between the ACC and other PFC regions such as the dorsolateral prefrontal cortex (DLPFC). Support for this notion is found in studies which demonstrate a high correlation between activation in these regions (Badre & Wagner, 2004; Carter et al., 1998; Kerns et al., 2004; Kiehl, Liddle, & Hopfinger, 2000). As such, primary functions in which the ACC is involved, such as response-monitoring, may be anticipated to reveal developmental differences throughout early childhood this brain region continues to mature in conjunction other prefrontal regions.

One way to pursue an investigation of ACC maturation in young children is through the use of psychophysiological methodology focusing on the relatively recent discovery of a specific event-related potential (ERP), called the error-related negativity (ERN). This component provides a direct measure of the neural systems underlying response-monitoring processes and prior research has revealed developmental increases in the amplitude of this component throughout adolescence into young adulthood (Davies et al., 2004; Ladouceur et al., 2007). Overall, research using this ERP methodology in children could enhance understanding of real time reactions to behavioral performance and help to illuminate the interactions between the supervisory portions of the PFC system and the limbic-linked ACC region. Furthermore, investigations of this nature would supplement current behavioral assessments of response-monitoring that have been used in the developmental literature.

Behavioral measures of response-monitoring

In addition to the ERN, there are several behavioral measures that assess an individual's capacity to monitor their ongoing response choices. Although some of these measures tend to portray only one component of response-monitoring at a time, these behavioral assessments still provide evidence that the response-monitoring process has been activated. One such measure is the overt behavior of self-correcting erroneous responses. Rabbitt (1966) found that adult subjects rapidly correct themselves after pressing the wrong button in a forced-choice selection task by immediately pressing the correct button. Response-monitoring in this context can be measured both for presence or absence of self-correction after an error and also for response time latency to implement the self-correction.

Another way of measuring response-monitoring in cognitive tasks (e.g. Stoop, fanker, go/no-go paradigms) is to examine response times on trials following incorrect trials as compared to response times following correct trials. If inaccurate performance is particularly salient to an individual, more controlled and slower responding in the trial following an error is typically exhibited (Davies et al., 2004; Henderson, 2003; Luu et al., 2000). This form of response-monitoring highlights the strategy adjustment component of the monitoring process in which subjects slow their reaction time after an error in order to maximize accurate performance on the upcoming trial. Several developmental studies that have assessed strategy adjustment indicate that children do have the ability to exhibit this aspect of the response-monitoring process in general, but that not all children display this reaction time slowing pattern (Davies, et al., 2004; Henderson, 2003; Jones, Rothbart, & Posner, 2003; Stins, Polderman, Boomsma, & de Geus, 2005). Additional variations of these response-monitoring assessments have also been examined in infants and preschoolers. For instance, in the process of learning from motor actions infants display a form of response-monitoring when they make repeated and eventually successful attempts at obtaining objects by varying their reliance on external forces involved in controlling and implementing appropriate arm movements (Konczak, Borutta, & Dichgans, 2004).

Interestingly, this early response-monitoring ability, which involves evaluation and adjustment of one's body in relation to objects, has been found to precede an infant's ability to coordinate multiple levels of sensory information in monitoring progress towards object retrieval (von Hofsten, Vishton, Spelke, Feng & Rosander, 1998). For example, Diamond (1991) has demonstrated that at 9-months of age infants reaching to retrieve an object from a box are completely dominated by visual information such that infants only focus on line of sight and continue to reach for an object they can see through the closed side of the box even if they accidentally happen to touch the object through the more obscure, but open, side. However, by 12-months of age infants have developed strategies that let them view an object from one direction but reach and retrieve it from another direction. This discrepancy in monitoring across ages suggests that an underlying neural system for response-monitoring may exist quite early in infancy, but it may continue to develop throughout childhood. Specifically, this development is postulated to occur in accordance with the growth of corresponding brain structures (i.e. the PFC), which contributes to more elaborate forms of regulatory abilities in children.

In preschool-aged children self-regulation has commonly been examined in the context of inhibitory control tasks, which require children to either withhold responses or produce incompatible responses such as simplified go/no-go paradigms like the Simon-Says game (Jones et al., 2003) or Luria's (1961; Diamond & Taylor, 1996) tapping task in which children are asked to generate a tapping sequence that contrasts the sequence performed by the experimenter. These types of tasks that focus on conflict situations often provide optimal conditions for assessing response-monitoring skills. Rather than preceding response-monitoring as predicted, Jones and colleagues (2003) found that children's inhibitory control develops in parallel with response-monitoring as demonstrated by increased performance accuracy and development of post-error slowing in a Simon-Says task for 4-year-old, but not 3-year-old, children.

The progression of increased behavioral response-monitoring over the course of childhood has also been found in verbal forms of response-monitoring in which children outwardly indicate recognition of an error. For example, in a study using the dimensional change card sort task (DCCS), 3-year-old children rarely self-reported errors (Jacques, Zelazo, Kirkham, & Semcesen, 1999). This verbal form of error detection is often referred to as private speech. Commonly exhibited in young children, private speech is language that is spoken solely for the benefit of oneself and helps in directing and regulating behavior. More specifically, private speech is hypothesized to facilitate the developmental transition from outward regulation to internal response-monitoring across early childhood (Vygotsky, 1934/1987; Winsler & Naglieri, 2003). Private speech is characterized as consisting of a variety of forms of verbal communication ranging from mere utterances to specific task-oriented directive speech (Berk, 1986; Winsler, Diaz, Atencio, McCarthy & Chabay, 2000).

Interestingly, the emergence of verbal response-monitoring strategies does not appear to map onto the emergence of other forms of response-monitoring. In the Simon-says task children were found to use physical as compared to verbal response-monitoring strategies in order to detect errors (i.e. immediate correction of an inaccurate motor response) and to enhance performance (i.e. physical restraint of an arm when arm motion was required to be withheld). Response-monitoring as evidenced by physical manipulation of oneself or objects has been demonstrated in infants (as mentioned previously) and toddlers also display response-monitoring via error detection and strategy adjustment in tower building tasks and other paradigms involving physical manipulation of objects (DeLoache, Sugarman, & Brown, 1985; Zelazo & Muller, 2002). Thus, assessment of response-monitoring may be task or domain specific, with varying paradigms differentially activating the response-monitoring process.

In accordance with this view, it has been hypothesized that monitoring strategies may be influenced directly by the form(s) of feedback that are provided to the child through the task itself (DeLoache et al., 1985). For instance, in paradigms using nesting cups, the action of manipulating the cups combined with the composition of the cups themselves inherently provides functional feedback that children can easily sense, such as lack of fit when children incorrectly attempt to place a bigger cup inside a smaller cup. The feel of resistance between cups that do not fit together provides feedback that the current action is an error and children utilize this knowledge to institute corrective action.

Using a nesting cup paradigm, DeLoache and colleagues (1985) found that all participants between the ages of 18-42 months were equally sensitive to error commission; however, there were developmental differences in the flexibility and extensiveness of correction strategies that children used to achieve their stacking goals. In contrast, other research using materials in which the task provided unambiguous feedback (i.e. stacking rings or graduated sticks) has found more simultaneous emergence of error detection and correction strategies (DeLoache et al., 1985; Wilkinson, 1982). Besides feedback based on material composition, it is also possible that task difficulty influences the degree to which task demands inform children of error commission. Specifically, if the task involves stacking rings and the child's goal is not to stack them in size, but rather to put them on the pole then the child will be less likely to detect the stacking error related to size (DeLoache et al., 1985).

Despite these attempts to qualify the emergence of and contributors to response-monitoring patterns in children, the question remains whether or not the previously mentioned assessments in children are tapping into the same monitoring systems that are examined in adults. A major difficulty in answering this question has been the need to assess very different types of outward behaviors in children and adults due to differing testing capabilities. As highlighted earlier, one alternative to a strict focus on behavioral assessments is to supplement these investigations with physiological measures in order to more precisely identify similarities and variations in the response-monitoring process.

Physiological measures of response-monitoring

The primary physiological measure related to response-monitoring is the error-related negativity (ERN). Time-locked to a subject's response, the ERN has a centromedial scalp distribution and imaging studies indicate that the ERN is generated within the ACC. In general, the ERN is part of a larger error monitoring system that is posited to influence the development of self-regulatory skills. As such, the ERN may serve as a feed forward control mechanism by which response-monitoring can influence future cognitive strategies and overall behavioral performance (Bernstein, Scheffers, & Coles, 1995; Rodriguez-Fornells, Kurzbuch, & Munte, 2002). Several research studies in adults suggest a moderately strong link between the ERN and error compensation such that individuals who had higher amplitude ERNs also had longer behavioral response latencies on correct trials following error trials (Gehring, Goss, Coles, Meyer, & Donchin, 1993; Scheffers et al., 1996).

There have been four primary theories regarding the ERN. The initial theory of ERN function was the error detection or mismatch detection theory (Coles, Scheffers, & Holroyd, 2001; Falkenstein, Hohnsbein, Joorman, & Blanke, 1990, 1991), and this view of the ERN centered on its role in the detection and correction of errors. While this notion is still discussed in the current literature, several other theories have recently emerged which differ in regard to the precise functions of the ERN. These include the conflict detection theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Yeung, Botvinick, &

Cohen, 2004) and the reinforcement learning theory (RL-ERN; Holroyd & Coles, 2002) which subsumes a number of the basic tenets of the previously described models.

The error detection theory evolved from notions focusing on a comparison process underlying the phenomena identified as the ERN. Falkenstein and colleagues (Falkenstein, Hohnsbein, Hoorman, & Blanke, 1990; 1991) initially conceptualized the ERN as correlated with error detection processes via response representations. In this view, the ERN is generated by the neural comparison of the executed response representation and the representation of the required response. This process involves three steps: 1) response determination (the representation of the required response is activated), 2) response choice (the representation of the actual response activated), and 3) comparison (the two response representations are compared). When the representation of the actual response is inconsistent with the representation of the intended response, a mismatch (error) is detected (see Figure 2). Later research tied these notions into a broad error-processing system comprised of a monitoring system and a remedial action system. The comparison process was viewed as central to the monitoring system and when an error signal arose it would be passed onto the remedial action system in order to inhibit or correct the inaccurate response and to potentially induce strategic adjustments such as response slowing on trials following the commission of an error (Coles, Scheffers & Holroyd, 2001; Gehring et al., 1993).

Support for the error detection theory comes from research investigating or manipulating both correct and incorrect response representations. One such study that used a four-choice reaction time task found the amplitude of the ERN to fluctuate in accordance with the degree of similarity or dissimilarity between actual and required response representations (Bernstein et al., 1995). Likewise, in paradigms with the following array of manipulations: sleep deprivation, enhanced visual loads, increased stimulus-response mapping variability, or degraded task stimuli, response representations were found to be altered and lead to variation in ERN amplitude based upon participant certainty (Scheffers & Coles, 2000; Scheffers, Humphrey, Stanny, Kramer, & Coles, 1999). Despite this line of evidence, the existence of a correct-response negativity (CRN) found on accurate response trials seems to indicates that the ERN reflects more than an error detection process and perhaps may serve a broader function of evaluating response patterns in general, regardless of paradigm conditions (Falkenstein et al., 2001; Vidal, Burle, Bonnet, Grapperon, & Hasbroucq, 2003; Vidal, Hasboucq, Grapperon, & Bonnet, 2000). This more expansive perspective merges well with the currently proposed model of response-monitoring and suggests that the narrow focus on inaccurate responding limits the applicability of the error detection theory.

Similar to the error detection theory, the conflict-monitoring theory (see Figure 3) also emphasizes a comparison process. However, the focus of comparison in this model is at the level of conflict and the ensuing need for engagement of top-down cognitive control. The conflict-monitoring theory also highlights the role of the ACC in on-going performance evaluation and hypothesizes that during response selection the ACC functions to detect conflict and to relay this information to other neural regions that directly implement cognitive control such as the PFC (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Carter et al., 1998). This theory centers on the premise that cognitive representations in the PFC compete for expression and the ACC serves to detect this conflict and indicate to the PFC which is the correct representation for the PFC to maintain. By signaling the need to more strongly activate certain representations, the ACC directs enhanced processing of those particular attention pathways. Thus the ACC is involved in top-down processing but it is not directly responsible for the allocation of attentional control (Cohen, Aston-Jones, & Gilzenrat, 2004). These ACC functions are supported by fMRI studies that reveal activation of the ACC on both incorrect and correct trials and in a variety of task conditions in which multiple responses compete for attentional allocation (Carter et al., 1998; Kiehl et al., 2000; Menon, Adleman, White, Glover, & Reiss, 2001).

Within the framework of a connectionist model (see Yeung, Botvinick, & Cohen, 2004 for model details), the conflict-monitoring theory also focuses on the ERN as an output of ACC activity and suggests that the ERN as results from response conflict after error commission due to continued stimulus processing. In contrast, the conflict processing on correct trials is thought to be processed prior to subject response and is evident not in the CRN but rather in a stimulus-locked ERP measure called the N200. As such, the amplitudes of the ERN and N200 are anticipated to be positively associated such that participants who are more sensitive to conflict monitoring would show this pattern across both correct (N200) and error (ERN) trials (Yeung et al., 2004). However, this association has not been consistently supported across studies (Davies, Segalowitz, Dywan, & Pailing, 2001) and further research is needed to reconcile the results that have been found using a variety of data processing techniques. The conflict-monitoring model differs from the error-detection theory by postulating that the ERN does not simply reflect the output of an error detection process, rather, the ERN may also function as an input for continued stimuli processing and further aids in solidifying the identity of the correct response representation (Yeung et al., 2004). This notion has lead to additional research as well as an increased focus on a related but distinct theory of ERN function called the reinforcement-learning model (RL-ERN; Holroyd & Coles, 2002; Holroyd, Yeung, Coles, & Cohen, 2005).

The RL-ERN (see Figure 4) attempts to integrate the electrophysiological study of action monitoring with the broad field of reinforcement learning. A benefit of this integration is the ability to examine the model at both the biological and the cognitive level while also allowing for assessment of questions regarding how the ERN may alter as a function of learning processes. Like the conflict-monitoring model, the RL-ERN theory is computationally based but in addition to addressing response conflict, this model also concentrates on the online detection of errors and denotes the progression from error detection to the production of the ERN. More specifically, while the conflict-monitoring theory hypothesizes that the ERN is a consequence of a discrete comparison, the RL-ERN theory proposes that the ERN is part of a continuous process of on-going monitoring (Willoughby, 2005).

Within this model the function of the ACC is to both filter sensory input and to propagate the error signal. The error signal itself is hypothesized to be generated by the basal ganglia, which serves as an ‘adaptive critic’ by processing incoming sensory information and predicting event-related outcomes and comparing them to actual outcomes. Discrepancies between these representations produce phasic shifts in the dopamine signal resulting in a temporal difference error. This error signal is distributed via the mesencephalic dopamine system to three locations: 1) the motor controllers of the system (i.e. amygdala, dorso-lateral PFC, orbitofrontal cortes), 2) the control filter (the

ACC), and 3) back to the adaptive critic (the basal ganglia). The phasic shifts of the dopamine signal among these locations disinhibits the ACC and modulates the magnitude of the ERN signal (Holroyd & Coles, 2002; Holroyd, Niewenhuis, Mars, & Coles, 2004; Holroyd et al., 2005).

Considerable research is still needed to fully understand the complex interactions between the various neural systems involved in the error-processing system according to the RL-ERN theory. Despite these unanswered questions, there is evidence to support the predictive validity of this model such that the ERN has been found to increase in amplitude as stimulus-response mappings are learned (i.e. Holroyd & Coles, 2002). Efforts have also been made to investigate the contribution of the mesencephalic dopamine system to the ERN signal. For example, in studies of older adults, ERN amplitude has found to be reduced although overall task performance does not show impairment (i.e. Nieuwenhuis, Ridderinkhof, Talsma, Coles, & Holroyd, 2002). In addition, a pharmacological study found that administration of a dopamine agonist enhanced the amplitude of the ERN response while administration of a dopamine antagonist, which inhibits ACC function, lead to a decrease in ERN amplitude (de Bruijn, Hulstijn, Verkes, Ruigt, & Sabbe, 2004). Evidence from certain clinical populations suggests that individuals with conditions that are known to interfere with the dopamine system, such as Parkinson's disease or schizophrenia, also display abnormal ERNs (i.e. Dolan et al., 1995; Falkenstein et al., 2001; Harrison, 2000; Holroyd, Praamstra, Plat, & Coles, 2002). Overall these results provide preliminary support for the RL-ERN theory notion that certain ACC functions, including the production of the ERN signal, are influenced by midbrain dopamine.

In line with the emphasis on continuous processing by the ACC, an additional hypothesis regarding ERN function emphasizes the limbic connections of the ACC (Luu & Posner, 2003; Luu & Tucker, 2001; Luu & Tucker, 2004; Luu, Tucker, Derryberry, Reed, & Poulsen, 2003). Although not as formally conceptualized as the previously mentioned theories, this affective regulation hypothesis of the ERN has been postulated for some time (Gehring et al., 1993; Gehring & Willoughby, 2002; Vidal et al., 2000) but has never fully been accounted for, or incorporated in existing ERN theories. Recently Willoughby (2005) has referred to these ideas as the emotional processing theory of the ERN and this terminology will be used throughout this paper.

The emotional processing theory (see Figure 5) proposes that the ERN reveals more than error detection or conflict. Specifically the ERN is hypothesized to reflect the ‘affective consequences’ of unexpected results such that mistakes or conflict produce emotional evaluations of expectancy violations (Luu & Pederson, 2004). Thus, the magnitude of the ERN is associated with affective distress generated by these emotional evaluations (Luu et al., 2000). Proponents of this theory have looked to the connection between the ERN and on-going theta rhythms (4-7 Hz band) as neural evidence that the ERN may reflect more than one component of ACC function (Luu et al., 2000; Luu & Pederson, 2004). In this manner, the ERN may actually reflect theta activity involved in coordinating learning and action-regulation processes throughout the limbic system (Luu & Pederson, 2004).

Both studies of motivational manipulation and affective predisposition provide support for the emotion processing theory of the ERN which would hypothesize that perturbations in the affective system would create corresponding variation in ERN production. For example, individuals high on the trait of conscientiousness display less variation in ERN amplitude across motivational manipulations of high and low reward (Pailing & Segalowitz, 2004), whereas individuals high in impulsivity display greater variability in ERN amplitudes across punishment versus reward conditions (Potts, George, Martin, & Barratt, 2006). In a set of investigations of emotionality, individuals who were high on negative affect and/or negative emotionality were found to display ERNs with larger amplitudes as compared to individuals low on negative affect and emotionality (Hajcak, McDonald, & Simons, 2004; Luu et al., 2000). However, Luu and colleagues (2000) also found that ERN amplitude varied within individuals high in negative emotionality as a function of task duration. Specifically, ERN amplitudes diminished for the group high in negative emotion as the task went on whereas the opposite pattern was observed for the low negative emotion group. This result suggests that individuals low and high in negative emotionality have different patterns of response-monitoring engagement.

Subtle differences have also emerged in the ERN literature when assessing individuals high in general anxiety and worry. For instance, undergrads who report high levels of obsessive-compulsive symptoms or general anxiety exhibit enhanced ERN amplitudes in response to errors but they also differ in their reactivity to correct trials as compared to control subjects (Hajcak & Simons, 2002; Hajcak, McDonald, & Simons, 2003). In contrast, individuals diagnosed with clinical levels of anxiety consistently demonstrate greater reactivity only to error trials and display significantly larger ERN amplitudes as compared to controls. For example, individuals with obsessive-compulsive disorder (OCD), exhibit significantly larger ERN amplitudes than matched controls

(Gehring et al., 2000). The amplitude of the ERN in individuals with OCD is also associated with symptom severity such that a higher level of symptom severity is related to enhanced ERN amplitudes. In addition, adolescents diagnosed with an anxiety disorder also demonstrate enhanced ERNs compared to age-matched controls (Ladouceur, Dahl, Birmaher, Axelson, & Ryan, 2006). Although results from both diagnosed and non-diagnosed samples suggest a hyper-activation of the neural system associated with response-monitoring (see Gehring et al., 2000), the clinical populations are more consistently identified by reactivity that is specific to error trials as compared to the non-diagnosed populations which exhibit heightened reactivity to both correct and incorrect responding.

Interactions between personality and task design have also been demonstrated which further emphasize the complexity of assessing individual differences in response-monitoring. For instance, Dikman and Allen (2000) found that subjects rated as low in socialization display smaller ERN's in conditions of punishment as compared to conditions in which they are rewarded for good performance. In another study, the emotional nature of the stimuli (i.e. happy or angry faces) interacted with participant's self-reported level of task anxiety. Specifically, high state anxiety individuals exhibited enhanced ERNs in response to errors on happy faces and smaller ERNs in response to errors on angry face stimuli (Compton, Carp, Chaddock, Fineman, Quandt, & Ratliff, 2007). The authors of this study suggest that reactivity to the commission of errors varies not only as a function of underlying personality but also as a product of individual differences in performance expectations.

Along these lines, recent work has conceptualized the ERN as representing the activation of defensive motivation responses. Hajcak and Foti (2008) demonstrate that individuals with large ERNs display significantly larger potentiated startle responses on the trials following an error, which indicates that error reactivity may prime defensive motivation. The notion that aversiveness to errors is indexed by the ERN has some support in the previously reviewed literature which highlights heightened error reactivity among certain groups of anxious individuals. Additional work examining Gray's (1982) personality traits of behavioral activation and behavioral inhibition, which are linked to approach and avoidance systems, respectively, also suggests that behaviorally inhibited individuals are sensitive to the commission of errors due to an underlying motivation to avoid punishment (Boksem, Tops, Wester, Meijman, & Lorist, 2006).

In sum, the variation in ERN results among individuals of varying personality traits suggests several complications associated with the emotion processing theory of the ERN. Above and beyond these ERN findings, a primary concern for this theory revolves around the basic question of whether emotion and cognition should be understood separately before being examined in conjunction. This question is not addressed within the confines of the emotion processing theory; however, it is clear that the ERN appears to index some level of the cognition-emotion interface and as such further refinement of the emotional processing theory may provide a meaningful context within which the neural mechanisms driving the relations between emotional reactivity and response-monitoring may be determined.

Overall, a strong debate still exists on these various theoretical functions of the ERN and these deliberations have generated a great deal of research in adults regarding this phenomenon. In contrast, the examination of the ERN response in young children is just beginning. Recent progress has been made in identifying developmental patterns of ERN expression across middle to late childhood. In two cross-sectional studies of ERN development, Davies and colleagues (2004) found that the expression of the ERN becomes more stable and prominent with age in subjects ranging from 7- to 25-years-old. Research focusing on the adolescent age range (Ladouceur et al., 2007; Santesso & Segalowitz, 2008) also demonstrates a development increase in ERN amplitude from early to late adolescence as well as into young adulthood. Combined, these results may index either maturation of the ACC region which underlies ERN expression or a delay in the recruitment of the ACC in the response-monitoring process (Ladouceur et al., 2007; Santesso & Segalowitz, 2008).

Although there are developmental differences in the absolute magnitude of the ERN amplitude between children and adults, work examining differences within the childhood age range also suggest that individual differences play a prominent role in children's response-monitoring. For example, children with high rates of obsessive-compulsive behaviors have larger ERN responses than children with low rates of these behaviors (Santesso, Segalowitz, & Schmidt, 2006). Situational context also influences children's response-monitoring such that greater ERN amplitudes are evident in children who completed a go/no-go task in the presence of a peer as compared to children who performed the task alone (Kim, Iwaki, Uno, & Fujita, 2005).

Differences in ERN amplitude have also been found when examining special populations of children. For instance, children with attention-deficit hyperactivity disorder (AD/HD) between the ages of 7 and 13 have more difficulty in timed discrimination tasks that use sets of incongruent stimuli and demonstrate differences in ERN amplitude when compared to controls (Jonkman et al., 1999; Burgio-Murphy et al., 2007). In particular, children with a combined AD/HD diagnosis exhibit ERN amplitudes that are significantly larger after incorrect responses as compared to controls. This somewhat unpredicted pattern for AD/HD children has been interpreted in terms of an attempt to maximize performance by enacting heightened response-monitoring. More specifically, AD/HD children may need to be more vigilant during a task in order to reach an average level of performance. These results imply that for children with specific characteristics, ERN variation may be closely connected to response-monitoring efforts.

In sum, the combination of the ERN data and the behavioral post-error slowing patterns in children indicate that children have the ability to react behaviorally and physiologically to error commission in a similar manner as adults. However, the physiological patterns of response-monitoring show clear developmental differences between children and adults in the magnitude of the ERN response. Furthermore, the consistency with which children engage in response-monitoring is also highly variable across task conditions and between age groups of children. As such, further work is needed to elucidate the manner in which children develop adult-levels of response-monitoring and a special emphasis should be placed on understanding variation in neural mechanisms such as the ERN which serve as a representation of a more automated form of response-monitoring.

Immediately following the ERN in the response-locked waveform, the error-related positivity (Pe) component is theorized to be involved in additional response processing, beyond error detection, at the level of subjective awareness (Neiwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). Similar to the ERN, the Pe is also closely tied to the ACC region (Herrmann, Rommler, Ehlis, Heidrich, & Fallgatter, 2004; van Veen & Carter, 2002) and appears to be composed of two sub-components. These subcomponents may be related to distinct areas of the ACC. An early Pe component emerges at approximately 180 ms after subject response and is maximal at Cz, whereas the later Pe peaks around 300 ms after response and is maximal at Pz (van Veen & Carter, 2002). The early Pe is theorized to reflect a basic rebound from the ERN whereas the late Pe is linked to individual differences in performance evaluation (van Veen & Carter, 2002).

More specifically, the late Pe component is associated with the rostal region of the ACC as opposed to the ERN and the early Pe, which are both linked with more caudal ACC involvement (van Veen & Carter, 2002). The rostal ACC region is active only during incorrect responding thus making the late Pe specific to errors (Kiehl et al., 2000; Menon et al., 2001). As such it has been speculated that the late Pe reflects a subjective and affective response to error commission. Current developmental evidence in children indicates that the late Pe amplitude is stable between middle childhood through young adulthood (Davies et al., 2004; Ladouceur, Dahl, & Carter, 2004; Segalowitz, Davies, Santesso, Gavin, & Schmidt, 2004). These data suggest that the mechanisms responsible for the expression of the late Pe are more fully developed by middle childhood than mechanisms responsible for the ERN in children.

The role of feedback in response-monitoring

In addition to internally generated detection and evaluation processes, external feedback may also be significantly involved in the adaptation and refinement of the response-monitoring mechanism. As noted earlier, Norman and Shallice (1986) postulated a cognitive ‘supervisory system’ model of self-regulation. This model emphasized the separation of two subsystems that are responsible for the execution of routine and non-routine cognitive activity. Non-routine activity involves top-down activation of cognitive structures relevant to complex information processing whereas routine activity does not. In order to distinguish between routine and non-routine activity the system must depend upon feedback to guide the appropriate cognitive activity (van der Molen, 2000). Although this particular model includes feedback as an important component in flexible cognitive and behavioral responding, it does not distinguish between internally and externally generated feedback evaluations nor does it explain how these evaluations serve or fit in with the response-monitoring process.

In a complementary model to the ‘supervisory system’ (Norman & Shallice, 1986), Stuss (1992) proposed a model that placed greater emphasize on the role of feedback. In Stuss’s model, a hierarchal development of information processing centers around three distinct levels: 1) sensory perception, 2) executive control, and 3) self-reflectiveness. Stuss (1992) suggests that these processing levels are connected via response-monitoring networks that act off of both feedback and feed forward loops. The efficiency of these networks and feedback loops is postulated to improve throughout childhood as children demonstrate a dramatic increase in their ability to utilize various forms of information, such as verbal and visual feedback, to modulate ongoing behavior in a manner that is reflective of an active self-supervisory system. This model specifically emphasizes response-monitoring as a significant factor in information processing; however, further research is needed to clearly document the developmental progression of efficiency in feedback utilization and to understand how response-monitoring can change as a function of different forms of feedback.

The current conceptualization of the response-monitoring process (see Figure 6) follows this notion of feedback loops. The model demonstrates the progression beginning with an initial response and traces the primary components of the mechanism. First, the response is detected and appraised at an automatic level. Second, once the basic situation has been assessed, a more thorough evaluation of the response outcome can be examined by determining the accuracy of that response in conjunction with task goals. This evaluation information feeds forward and if the response is line with one's conceptualization of efficient responding, then the current approach to the task will be maintained. However, if the response is determined to be at odds with task goals, strategy adjustments can be enlisted and tested on the following response. Internal feedback, which involves both the appraisal and evaluation segments of the response-monitoring mechanism, helps one advance through the response-monitoring process.

In addition, external feedback is also hypothesized to influence (i.e. enhance or alter) the typical response-monitoring process (see Figure 7). When children are left to their own devices, they are forced to rely on internal evaluation of their own performance for feedback and guidance on future behavior. However, when external feedback is provided children have an additional opportunity to re-assess and modulate their future responding. It is hypothesized that the response-monitoring process is particularly influenced by external feedback during the segments of strategy adjustment or strategy maintenance.

Over time, children get better at processing external forms of feedback and can then incorporate this information into their own internal model of acceptable behaviors and consequences. This transition is thought to assist older children implement the appropriate response evaluation and strategy adjustment segments of the response-monitoring process, even in the absence of external feedback. In contrast, younger children who are still refining their response-monitoring mechanism are more likely to need assistance when attempting to activate these skills in high-demand situations (i.e. conflict or time-pressure scenarios).

Feedback, either internally or externally generated, is crucial to the development of the response-monitoring process because it impacts future response strategies by providing information regarding task performance. In addition, feedback can carry more than just neutral information. According to Derryberry (1991), feedback can potentially trigger emotional arousal based on self-judgment of performance. This concept of feedback activating emotional systems corresponds to notions of affective influences on self-regulation patterns. For example, in Gray's arousal theory (1982), two primary emotional systems (Behavioral Inactivation System: BIS and the Behavioral Activation System: BAS) can act to modulate arousal, attention, and response processing. As such, feedback may influence future performance depending upon the interaction between the valence of the feedback message and an individual's emotional response style.

Research also suggests that higher order cognitive functions (i.e. response-monitoring) and emotion can be integrated (Gray, Braver, & Raichle, 2002; Gray, 2004).

Emotions are thought to help delineate the need for reprioritization of behavior (Simon, 1967), with stronger emotions signaling a more immediate response need (Carver, 2004). Therefore, feedback that elicits an emotional response may significantly contribute to enhanced cognitive processing. However, it is currently unknown how this potential enhancement effects the maturation of these cognitive processes. When considering the basic emotion distinction of negative versus positive affect, it has been argued that negative affect has a stronger impact on cognitive processing compared to positive affect, due to its enduring effects (Larsen & Prizmic, 2004).

The contribution of temperament to response-monitoring

Another potential factor in the development of children's response-monitoring patterns is temperament. Temperament reflects affective and motivational biases that influence both the processing of and reactivity to sensory stimuli and environmental contingencies. First investigated by Thomas and Chess in the early 1960's, temperament is broadly conceptualized as variations in levels of children's emotionality, impulsive activity, and reactivity (Buss & Plomin, 1984; Kagan, Reznick, Clarke, Snidman & Garicia-Coll, 1984; Rothbart, 1981). More specifically, temperament is defined as "behavioral styles that appear early in life as a direct result of neurobiological factors" (Fox & Henderson, 1999, p. 445). Due to differences in emotional sensitivity and cognitive/behavioral reactivity, temperament has been noted to play a major role in behavioral regulation skills (Eisenberg et al., 2001; Fox & Henderson, 1999).

The relation between specific personality factors and response-monitoring has previously been demonstrated in research conducted with adults (i.e. Hajcak et al., 2003, 2004; Luu & Tucker, 2001). As noted earlier, these studies found that response strategy, level of task engagement, and response-monitoring were related to negative and fearful affect. In addition, Henderson's (2003) investigation of children 6- and 7-years-old found ERN amplitude to be negatively related to the temperamental trait of inhibitory control. According to Rothbart (1989), inhibition can be displayed both actively and passively. Passive inhibition is related to fearful behavior and anxiety whereas active inhibition involves effortful control processes that are utilized to manage various forms of impulsive behavior. Across the preschool time period children improve in delay of gratification and conflict tasks, each of which require high levels of inhibitory control (Carlson & Moses, 2001; Gerstadt, Hong, & Diamond, 1994; Kochanska, Murray, Jacques, Koenig, & Vandegeest, 1996). As they progress through early to middle childhood, children demonstrate a marked capability to perform higher levels of inhibitory control, thus making inhibition an important contributor to the emergence of successful self-regulation and in particular, behavior monitoring skills. Thus, inhibitory control is influential in both cognitive and emotional development (Kochanska et al., 1996). However, further research is needed to determine the extent to which individual differences in temperament influence cognitive processes such as response-monitoring.

Although children generally exhibit increased inhibitory control with development, there are still individual differences in regulatory performance expressed by children of different temperaments at various age points. For example, Gonzalez and colleagues (Gonzalez, Fuentes, Carranza, & Estevez, 2001) have found that temperament measures of emotionality and regulation are predictive of performance on tasks that assess susceptibility to stimuli interference (i.e. flanker and Stroop tasks). Specifically, children scoring higher in negative affect were found to experience greater difficulty with resolving conflict among similar stimuli, while children rated as low in inhibitory control exhibited greater difficulty when attempting to switch flexibility between different response conditions. These effects were most pronounced for girls as compared to boys, indicating that the developmental pathways of regulatory skills may vary by child gender (Gonzalez et al., 2001).

Furthermore, combinations of affect and inhibitory control are associated with different behavioral patterns referred to as externalizing or internalizing behaviors. Externalizing behaviors are patterns of reactivity associated with exuberant, aggressive, or conflict-ridden interactions with others, whereas internalizing behaviors are associated with anxiety, difficulty initiating or maintaining social interactions, and depression (Eisenberg & Fabes, 1992; Eisenberg et al., 2001). Davis and colleagues (2003) have found that children who have difficulty with externalizing behaviors that are related to low inhibitory control and high positive affect also exhibit poor attentional focusing and response control. Similarly, children classified as having internalizing problems also exhibit difficulty with regulation of attention but exhibit less impulsive behavior than children with externalizing problems (Eisenberg et al., 2001). Children high in internalizing behaviors also have high levels of temperamental negative affect (Fox, Hane, & Perez-Edgar, 2006; Rothbart, 2004).

Recently, several studies have begun to examine the question of personality or temperament differences and ERN expression in older children. Santesso and colleagues (Santesso, Segalowitz, and Schmidt, 2005) used the Junior Eysenck Personality Questionnaire with 10-year-olds and found similar patterns for the relation between personality and ERN expression in adults. Specifically, children low in socialization exhibited ERNs of smaller amplitudes. Henderson (2003) has also found connections between temperament assessments of inhibitory control and ERN expression such that children scoring lower in inhibitory control had smaller ERNs. Taken together, these results suggest that in addition to the development of neural substrates underlying response-monitoring processes, individual differences influence children's ERN patterns in a manner similar to that seen in adults. However, further research is needed to determine how individual differences interact to enhance or impede the response-monitoring process.

Interactive modulation of response-monitoring

The interaction between an individual's temperament and response processing can be further examined from a psychophysiological perspective by investigating an ERP called the feedback related negativity (FRN). Similar in magnitude to the ERN, but time-locked to the onset of external performance feedback, the FRN is also hypothesized to be part of a larger neural system of error detection (Miltner et al., 1997). In fact, evidence from dipole source localization studies suggest the ACC is the common source of generation for both the ERN and FRN (Dehane, Posner, & Tucker, 1994; Gehring & Willoughby, 2002; Holroyd, Dien, & Coles, 1998; Miltner et al., 1997) and fMRI data further indicate that a specific region in the dorsal ACC is activated for error responses and error feedback (Holroyd, Nieuwenhuis, & Yeung, 2003).

Many FRN have focused on how this measure varies depending upon the content of the feedback message itself. For example, undergraduates who were given a delayed feedback paradigm in which they were presented with feedback indicating extremely poor performance had greater FRN amplitude than in conditions where feedback indicated acceptable to good performance (Luu et al., 2003). Yeung and Sanfey (2003) also found the FRN to vary across task blocks with different ranges of monetary rewards. Specifically, within the framework of large gains and losses, a large loss resulted in FRN amplitudes of approximately the same size as small losses in the context of small gains. This pattern of relative ranking for favorable or unfavorable outcomes is supported by a study of Holroyd and colleagues (Holroyd, Larsen, & Cohen, 2004) that found that losing the maximum reward was always judged to be the worst outcome and was associated with the largest amplitude FRN.

In particular, studies of this nature fit well with the reinforcement-learning theory (Holroyd & Coles, 2002), which emphasizes the role of the mesencephalic dopamine system as carrying a reward prediction signal (Schultz, 1998, 2002) that contributes to the production of the ERN and FRN. Further support for this theory is also found in paradigms which compare conditions of known stimulus-response mappings and conditions where the stimulus-response mappings need to be learned during the task. In studies where the connections are predictable, the system produces an ERN, whereas in conditions for which the mappings are unknown, subjects must rely on external feedback and thus generate an FRN (Nieuwenhuis, Holroyd, Mol, & Coles, 2004). Therefore, these results indicate that in addition to sensitivity to gains and losses, the FRN is also linked to learning proper response patterns.

However, it is not yet clear how different personality characteristics influence the expression of FRN and future research should determine whether it is related to both the behavioral and physiological measures of response-monitoring. Another concern is how the system transitions from dependence on external feedback and production of the FRN to being focused on internal monitoring and production of the ERN in conditions in which stimulus-mappings are predetermined and subjects are also presented with performance accuracy feedback. Developmental investigations of both ERN and FRN may provide insight into how various neural evaluative mechanisms work in conjunction with one another and individual characteristics in order to produce evaluative and regulatory behavior.

In sum, associations between specific personality factors and response-monitoring have previously been demonstrated in research conducted with both adults and children (i.e. Henderson, 2003; Santesso et al., 2005; Luu & Tucker, 2001). As noted earlier, these investigations found that response strategy, level of task engagement, and response-monitoring are differentially related to negative and anxious affect as well as inhibitory control. However, the nature of these associations varies depending upon the sample and the task requirements. These inconsistencies within the response-monitoring literature also represent the complicated nature of emotion-cognition interactions and highlight the need for detailed investigations of individual differences in response-monitoring. Taken as a whole, the current literature suggests the need for more comprehensive investigations into the role of affect, as assessed via temperament or personality differences, in influencing the development of active cognitive processing and resulting behavioral regulation outcomes.

In order to establish more powerful models of the connections between cognitive and affective processes, it is important to identify mechanisms that can be examined at both a physiological and behavioral level. The ERN, Pe, and FRN are three examples of neural mechanisms that can be investigated in this manner. Overall, how these physiological correlates of response-monitoring evolve in early childhood is still unclear and future research should focus on current gaps in the literature regarding the precise functional significance of these components in populations of various ages and personality characteristics. Addressing these questions may help to establish a better understanding of the relation between internally and externally guided response-monitoring patterns. Thus, the proposed project will extend the current research literature on children's response-monitoring patterns by examining the impact of specific task conditions (i.e. no-feedback versus no-feedback) on young children's behavioral and physiological correlates of response-monitoring while also accounting for individual differences in temperament.

Overview of the Current Study

Purpose

Developmental research on the neural basis of cognitive response-monitoring is limited in both the number of studies conducted and the age of children examined. Also excluded from the current response-monitoring literature is the utility of performance feedback on the expression of response-monitoring in young children. The age of participants (approximately 7-years-old) was selected for three reasons. First, seven year-olds have passed through a large developmental shift in regulatory ability associated with the three- to five-year age period. This shift makes 7-year-olds capable of longer periods of on-task behavior and better motor control, which corresponds cleaner ERP data.

Second, it is important to note that regulation skills are not fully developed in this age group. So although seven-year-olds have the skills necessary to methodologically complete the study, they also provide a unique window of insight to the continuing development of regulatory skills in young children. Lastly, the focus on this age group avoids previously reported pre-pubertal changes in the response-monitoring ERPs which appear as early as nine-years of age in females (Davies et al., 2004). In sum, this study aimed to establish normative patterns of response-monitoring in early childhood within the context of a flanker paradigm and to determine the effect of external feedback on the expression of children's behavioral and physiological correlates of response-monitoring.

Prior research has also established the significance of individual differences in affect on task motivation and response-monitoring performance among older children and adults (i.e. Henderson, 2003; Luu & Tucker, 2001; Santesso et al., 2005). However, the influence of various temperamental traits on the initial expression of response-monitoring in young children remains unclear. Following the conceptualizations of the previously mentioned theories, it was anticipated that temperamental differences would correspond to variations in the response-monitoring process. As such, this study examined whether differences in emotional reactivity and regulation as assessed via child temperament alters the expression of behavioral and physiological markers of children's response-monitoring during a flanker task using conditions with and without feedback.

Study Design

Children performed a modified flanker task where they were instructed to respond as quickly, and also as accurately as possible, to a series of stimulus arrays consisting of rows of arrows by pushing a button (see Laboratory Tasks description of the Flanker Paradigm). For half of the trial blocks children did not receive performance feedback and for the other half of trial blocks children were presented with external feedback for trial-by-trial performance accuracy. The feedback was presented visually immediately following subject response and consisted of a 1-inch yellow circle smiling (accurate response) or frowning face (inaccurate) located in the center of the computer screen. The presentation order of the task conditions was counterbalanced across participants.

Both behavioral and physiological correlates of the response-monitoring process were collected. The response-monitoring component of strategy adjustment was evaluated behaviorally by comparing reaction times on trials following an error to reaction times following correct trials. Physiological measures of response-monitoring were the amplitudes of the ERN, late Pe and the FRN. Maternal report of children’s temperamental shyness and inhibitory control were included as between-subjects variables (high versus low shyness or inhibitory control groups) in order to examine the potential influences of temperament traits on behavioral and physiological measures of response-monitoring.

CHAPTER III: METHOD

Participants

A total of seventy-four typically developing school aged children participated in the study (*M* = 7 years, 5 months; range = 6.4 to 8.9; *SD* = .72; 35 males, 39 females). Participants were recruited by obtaining a list of names and addresses of families with young children located in the Washington D.C. region near College Park, Maryland from an independent mailing company. Families were first contacted by mail with a recruitment letter and General Information Survey (see Appendices A and B) that requested information about the birth of their child and included questions on method of delivery, birth complications number of days in the hospital, and any illness or medical problems. Children who matched the age range for this study and who did not experience any birth complications (i.e. prematurity or peri-natal asphyxia), congenital or serious neurological disorders, or serious illnesses were contacted via phone. Families who agreed to participate were scheduled for a visit to the Child Development Laboratory.

The final sample consisted of primarily right-handed, Caucasian children from middle-to upper class socio-economic standing. Specifically, the racial/ethnic backgrounds of the families were 56% Caucasian, 20% African-American, 11% Hispanic, 5% Asian, and 8% other or mixed composition. The majority of children were first-born or second-born (53% and 37% respectively), and the remaining 10% were third-born or later. Education levels for mothers consisted of 16% high-school graduates, 41% college graduate and 43% percent had completed graduate school. Education levels for fathers were as follows: 20% high school graduate, 24% college graduate, and 56%

completed graduate school. Mothers worked an average of 36.4 hours per week (range = 5 to 62, *SD*=12.9) while fathers averaged 42 hours per week (range = 5 to 75, *SD*=8.6).

Procedures

Upon arrival to the Child Development Laboratory, the parent and child were shown to the psychophysiology testing room. At this time the purpose of the visit was discussed and the parental consent form was gone over in detail. The experimenter also read an assent form with the child describing the procedures and encouraged the child to ask questions. After filling out the necessary paperwork, the parent remained seated in the far corner of the room and worked on the demographics and temperament questionnaires while the child was situated in the testing chair and prepared for psychophysiological data collection. During this time the child either watched a video or read a children's magazine (approximately 10 minutes). Baseline EEG was then collected for 6 minutes (3 minutes eyes open, 3 minutes eyes closed). The child was then instructed on how to play the computer task (the flanker paradigm) and completed a practice block and four test blocks. Short breaks (approximately 2 minutes) were taken in between each block to allow the child to stretch their fingers and thumbs and talk with the experimenter. A longer break was provided in between the two task conditions in order to minimize possible fatigue effects (approximately 5 minutes). Each block of the flanker task took approximately 6 minutes to complete for a total of 24 minutes of testing and 8 minutes of rest. At the conclusion of the computer task, each child was allowed to choose a small toy from a prize box (e.g. a lego set, markers, or a jumprope) and the parents received $20 as a thank you for their participation. On average, the entire visit lasted approximately 1.5 hours.

Measures

The General Information Survey. This questionnaire was used in subject recruitment. It assesses demographic variables as well as children's emotional and health history, and parental interest in the study (see Appendix B).

Children's Behavior Questionnaire (CBQ; Rothbart, Ahadi, Hershey, & Fisher, 2001). The CBQ was used to assess child temperament. This measure is based on parental ranking of various child behaviors. Specifically, parents are asked to rate a series of socio-emotional behavior statements and indicate how reflective, or not reflective, that statement is of their own child by choosing from a range of rankings that span a 7-point rating scale. On this scale a response of '1' indicates 'extremely untrue' and a response of '7' corresponds to 'extremely true. There is also an option for 'NA' (not applicable) if parents are unable to make a judgment on a particular statement. There are a total of 195 questions which are used to create 15 temperament subscales (alpha coefficients range from .67 to .94). Of particular interest to this study is the Inhibitory Control subscale (alpha of .74), which examines the child's ability to inhibit inappropriate responses under specific instruction and novel situations. Also of interest is the Shyness scale (alpha = .74), which assesses a child's wariness of social stimuli or contexts. Items used to create the shyness and inhibitory control dimensions of temperament are listed in Appendix C.

Modified Flanker Paradigm (Eriksen & Eriksen, 1974). The flanker paradigm assesses an individual's ability to inhibit predominant response biases in the face of interfering stimuli. For the proposed study a modified flanker task with a stimulus array of arrows was used to assess children's physiological and behavioral responses to the commission of errors. Children were seated in front of a computer monitor and asked to hold a small box with two pushbuttons which were located on the upper portion of the box. The goal of the task was to have subjects respond to the central target arrow by pressing the corresponding button (right or left) regardless of the direction of the flanking arrows.

Trial blocks contained both congruent trials and incongruent trials. For congruent trials the target was flanked by identical stimuli and for incongruent trials the flanking stimuli were facing the opposite direction of the target. There were two kinds of congruent trials, 1) a row of arrows all facing right (>>>>>), or 2) a row of arrows all facing left (<<<<<) , and there were also two kinds of incongruent trials, 1) an arrow facing right in the middle surrounded by arrows facing left (<<><<), or 2) a left facing arrow in the middle surrounded by arrows facing right (>><>>). Trials began with the presentation of a warning cue (*****) for 500 ms, followed by a blank screen and then the presentation of the target display for 1000 ms and then another a blank screen for 500 ms. In the no-feedback condition the blank screen was extended for an additional 700 ms whereas in the feedback condition participant's accuracy on the current trial was reported via a smiley or frowning face during the 700 ms.

Children were required to respond within 1500 ms of the presentation of the target array. The difficulty level was controlled through variation of the presentation speed of the primary flanker targets. Depending upon participant accuracy, presentation time sped up, slowed down or remained the same in correspondence to the participant's current error rate. This manipulation resulted in an overall average error of commission rate of approximately 28%.

Prior to beginning the task, children were shown exemplars of the various target displays and asked to indicate that they understood the concepts of ‘right’ and left’ as well as ‘middle’. Children were then instructed to respond as quickly and correctly as possible by pressing a button that matched the middle arrow within the row of arrows. A set of 20 practice trials was completed prior to beginning the task to verify children’s understanding of the task and to allow the children to become familiar with the computer apparatus. Task instructions are presented in Appendix D.

Stimuli presentation was controlled by computer software (Cognitive Activation System; CAS, James Long Company, Caroga Lake, NY) run on an IBM PC on which the flanker task was programmed. Measures of response time and response accuracy per trial were directly recorded by STIM program software. The test portion of the task consisted of both no-feedback and feedback conditions presented in two blocks of 100 trials each for a total of 400 test trials. Participants were given short breaks in between test blocks within a condition as well as a longer break between condition blocks. The order of condition presentation was counterbalanced across participants (AB-AB or BA-BA) and the entire task took approximately 30 minutes to complete.

Electroencephalogram (EEG) Collection and Recording. During the flanker task brain activity was recorded by placing a stretchable lycra cap with sensors on the subjects head. Exfoliating and conducting gel were inserted into the sensors on the cap in order to assure good conductance and a clear EEG reading. EEG recording was taken from 15 sites: F3, Fz, F4, C3, Cz, C4, T7, T8, P3, Pz, P4, O1, O2, A1, and A2. These sites were referenced to Cz and AFz served as the ground electrode. Impedances were kept at or below 10 kilo-ohms. A separate channel was used to assess electrooculogram (EOG) recording from two mini-electrodes, one placed on the outer canthus and one placed on the supra orbit (above) the right eye, in order to monitor blinks and artifact score the ERP data. Both EEG and EOG leads were amplified by SA Instrumentation Bioamplifiers by factors of 5000 and 1000 respectively. Filter settings were set at 0.1 Hz (high pass) and 100 Hz (low pass). Data were digitized on-line with customized acquisition software and were sampled at a rate of 512 Hz with an Iotech Daqbook A/D converter.

EEG Analysis. The EEG was artifact scored with the ERP Analysis System (James Long Company, Caroga Lake, NY). Epochs containing signals +/- 200 μV were excluded from analyses and eye movement artifact was regressed. Trials with reaction times of less than 300 ms were excluded from analyses due to the possible confounds of anticipatory responses or stimulus component overlap (Hajcak, Vidal, & Simons, 2004).

To assess the ERPs all data channels were baseline corrected using a window from –200 to –100 ms prior to the children's response and were digitally refiltered with a 15-Hz low-pass filter. All ERPs were scored scored at frontal, central and parietal midline sites (Fz, Cz, & Pz). The ERN was defined as the negative most deflection in a -50 to 150 ms window of time after the button press whereas the Pe was scored as the positive most deflection the 100 to 250 ms window following button press. The FRN was scored in the feedback condition and was defined as the negative most point falling between 250-450 ms following feedback presentation.

Temperament Groups

Parental report was assessed on both the inhibitory control scale and the shyness scale. One parent declined to fill out the temperament questionnaire; therefore the following analyses are based on data for seventy-three children. Inhibitory control ratings ranged from 2.67 to 6.67 (*M* = 5.16, *SD* = .90) and the shyness ratings ranged from 1.00 to 6.00 (*M* = 3.36, *SD* = 1.41). The two scales were not related (*r* = .05, *ns*), indicating unique dimensions of temperament. Both scales were also independent of age and gender.

To examine individual effects of temperament, children were median-split into high (n = 37) and low groups (n = 36) for both the shyness and inhibitory control dimensions. Interactions between the two dimensions were also examined which resulted in the creation of four temperament groups: low shyness/low inhibitory control (n = 18), high shyness/low inhibitory control (n = 18), low shyness/high inhibitory control (n = 18), and high shyness/high inhibitory control (n = 19; see Table 1 for descriptive information). Temperament groups differed on mean ratings of shyness and inhibitory control (*F*'s (3,72) ≥ 34.15, *p*'s < .01) and follow-up analyses revealed that the differences were localized within temperament dimension (e.g. the two groups low in shyness differed from the two groups high in shyness but the low shy groups did not differ from each other, see Table 1). Children's classification into the temperament groups occurred with equal probability ($\chi^2(1) = .01$, *ns*) and was not related to age (*F*(3,72) = .16, *ns*) or gender ($\chi^2(3) = 1.42$, *ns*).

Summary of Hypotheses

Behavioral Measures

First, it was predicted that all subjects would have longer reaction times for blocks in which performance feedback was provided. This effect was hypothesized to result from increased vigilance toward response accuracy as prompted by the continuous performance feedback. Second, it was hypothesized that reaction times following incorrect trials would be slower than reaction times following correct trials, particularly in the feedback condition. Both hypotheses predicted that children's task performance would benefit from external feedback.

Third, temperament was predicted to influence response-monitoring such that children high in shyness, as compared to children low in shyness, would exhibit enhanced reaction time slowing during both task conditions (no-feedback and feedback). In contrast, the opposite patterns was predicted in relation to inhibitory control ratings such that high inhibitory control children were hypothesized to demonstrate minimal differences in post-error slowing across conditions and children low in inhibitory control were anticipated to display significantly greater post-error slowing in the feedback as compared to the no-feedback condition. An interaction between temperament dimensions was also predicted such that children high in shyness and high in inhibitory control were predicted to demonstrate the most consistent behavioral monitoring across conditions whereas the children low in both shyness and inhibitory control were expected to display the greatest variation in monitoring between task conditions.

Physiological Measures

In general, all children were anticipated to exhibit the primary physiological components of response-monitoring. However, individual differences were expected in the relation between the components across blocks such that children who display a small ERN in the no-feedback condition would be more likely to display a larger FRN in the feedback condition. Likewise, within the feedback condition children who exhibited a large ERN response were anticipated to display a smaller FRN response. No relation was hypothesized between the ERN and Pe across conditions; however, the Pe was expected to correlate negatively with the amplitude of the FRN for the feedback condition. For the connections between physiological and behavioral assessments of response-monitoring, it was predicted that reaction time slow following an error during the no-feedback condition would correlate with greater ERN responses whereas post-error slowing during the feedback condition was predicted to correspond to the FRN response.

It was further postulated that high shy children would generate a larger ERN than low shy children, regardless of condition. Moreover, this pattern was anticipated to be more pronounced during the feedback condition and it was also anticipated to carry-over to the Pe response such that high shy children were predicted to have larger Pe responses, particularly in the feedback condition. Although the FRN was only assessed in the feedback condition, a comparable amplitude pattern was expected. Specifically, children higher in shyness were hypothesized to exhibit a more negative FRN.

Similarly, children high in inhibitory control were expected to have larger ERP responses to the commission of errors than low inhibitory control children; however, this difference was anticipated to be evident primarily for the no-feedback condition. Again, the combination of high shyness and high inhibitory control was postulated to induce to the strongest levels of response-monitoring as evidenced via greater ERN, Pe and FRN amplitudes.

CHAPTER IV: RESULTS

Behavioral Performance

Statistical Analyses. To examine behavioral performance a series of repeated measures analyses of covariance (ANCOVAs) was conducted. Condition (no-feedback or feedback), and when appropriate, trial type, were the within subjects variables. Gender and condition order served as the between subjects variables and age was mean centered and then entered as a covariate (see Delany & Maxwell, 1981 for a review of handling covariates in repeated measures analyses). After confirming that condition order did not have main or interactive effects for any of the behavioral outcomes the analyses were re-run omitting this factor. The temperament ratings of shyness and inhibitory control were then examined in relation to behavioral performance by median-splitting the scores for each dimension (i.e. low/high shyness and low/high inhibitory control) and these groups were then added as separate between subjects variables to the ANCOVAs.

Three children were excluded from the analyses due to non-compliance on the flanker task (greater than two standard deviations above the mean on errors of omission) and an additional child was excluded due to missing temperament data. Behavioral analyses on accuracy rates and reaction times were conducted on the remaining 70 participants (32 male, 38 female; mean age = 7.5, *SD* = .71).

General Performance. The average error rate was 27.2% (*SD* = 11.6) and older children committed fewer errors than younger children ($F(1,67) = 10.29$, $p < .01$, $\eta_p^2 = .13$; $r = -.39$, $p < .01$). A two-way Trial Type x Condition interaction ($F(1,65) = 9.62$, $p < .01$, $\eta_p^2 = .13$) specified that children made fewer errors of omission in the feedback condition than in the no-feedback condition ($M = 4.1$ % and $M = 6.4$ %, respectively;

($t(69) = 3.93$, $p <.01$). This result suggests that trial-by-trial feedback helped children focus on performing the task.

For reaction time patterns, a main effect again emerged for condition ($F(1,65) = 13.92$, $p < .01$, $\eta_p^2 = .17$) with faster responses in the feedback ($M = 650$ ms) as compared to the no-feedback condition ($M = 682$ ms). Both age ($F(1,65) = 10.09$, $p < .01$, $\eta_p^2 = .13$) and gender ($F(1,65) = 11.67$, $p < .01$, $\eta_p^2 = .13$) were also related to average reaction times across conditions such that older children responded faster than younger children and males were faster responders than females ($M = 624$ and $M = 708$ ms, respectively; see Table 2 for a summary of behavioral results). Due to the associations between age, gender and task performance, both age and gender were controlled for in all further analyses.

The temperamental dimensions of shyness and inhibitory control were not related to overall accuracy rate on the task however differences did emerge for error type. Specifically, a three-way Trial Type x Condition x Inhibitory Control interaction ($F(1,61) = 4.62$, $p < .05$, $\eta_p^2 = .07$) revealed group differences in the patterns of errors of commission (wrong button press) versus errors of omission (no button press) across task condition. Although both groups decreased their errors of omission in the feedback block (t's$(34) \geq 2.63$, p's $\leq .01$), children low in inhibitory control also increased in errors of commission the feedback condition ($t(34) = -2.86$, $p < .01$; see Figure 8). Thus feedback may have triggered an increase in task engagement without a corresponding increase in performance accuracy for children low in inhibitory control.

Flanker Interference Effects. Overall, participants exhibited typical flanker interference effects as evidenced by accuracy and reaction time differences between congruent and incongruent trials. For accuracy, children were significantly more likely to respond correctly on congruent (*M* = 87%) as compared to incongruent trials (*M* = 58%; $F(1,67) = 279.69$, $p < .01$, $\eta_p^2 = .81$). This pattern was further defined by a three-way Trial Type x Condition x Shyness interaction ($F\ (1,61) = 4.57$, $p < .05$, $\eta_p^2 = .07$) which revealed that children low in shyness displayed higher accuracy rates on incongruent trials in the feedback condition as compared to incongruent trials in the no-feedback condition ($t(34) = 1.82$, $p = .08$). In contrast, high shy children did not differ in their incongruent trial accuracy rates across conditions ($t(34) = -.91$, *ns*). Thus, feedback reduced interference effects for low, but not high, shy children (see Figure 9).

For reaction time patterns, children responded faster on congruent (*M* = 623 ms) as compared to incongruent trials (*M* = 712 ms; $F(1,67) = 187.02$, $p < .01$, $\eta_p^2 = .74$), confirming greater processing demands for the incongruent stimuli. This trial type reaction time difference was further elaborated by a Condition x Inhibitory Control x Shyness interaction ($F(1,61) = 4.77$, $p < .05$, $\eta_p^2 = .07$) which revealed greater reaction time differences on incongruent trials across the no-feedback and feedback conditions for both low shy/low inhibitory control children and high shy/high inhibitory control children ($t's(17) \geq 2.48$, $p's \leq .05$; see Figure 10). In other words, these children demonstrated the largest decrease in interference effects between the no-feedback and feedback conditions as assessed by incongruent trial reaction times.

In sum, the current study was able to elicit typical interference effects on a modified flanker task. Furthermore, these behavioral patterns were also moderated by temperament style and task content (feedback versus no-feedback). Specifically, feedback appeared to be particularly helpful for processing and responding to complex stimuli (i.e. incongruent targets), especially for children of specific temperamental styles.

Post-Response Reaction Time. To examine children's compensatory responses to errors, reaction times following error trials were compared to reaction times following correct trials. Only correct trials following either errors or correct responses were included in the analyses (i.e. reaction times on errors that followed the commission of an error were excluded from the analyses). An additional five children were removed from the analyses because of too few errors of commission. Specifically, children with fewer than 10 errors of commission in either the no-feedback or feedback conditions were excluded. Reaction times analyses were conducted on the remaining 65 participants (29 male, 36 female; mean age = 7.5, *SD* = .69).

A two-way Trial Type x Condition interaction ($F(1,62) = 10.94$, $p \leq .01$, $\eta_p^2 = .15$) revealed the typical pattern of reaction time slowing in the feedback condition ($t(64) = -2.11$, $p < .05$) however, the opposite pattern emerged for the no-feedback condition ($t(64) = 1.96$, $p \leq .05$; see Table 3) with faster responses following errors. No associations emerged between the temperament groups and post-error reaction time patterns.

Psychophysiology Performance

Statistical Analyses. A series of repeated measures ANCOVAs was conducted to examine physiological response monitoring components. Preliminary analyses confirmed the lack of a condition order effect and this variable was removed from further analyses. The ERN and Pe were each assessed separately at the frontal, central and parietal regions with condition (no-feedback or feedback) and trial type (correct versus incorrect) as the within subjects variables. Gender served as the between subjects variable and age was mean centered and then entered as a covariate in accordance with Delany and Maxwell (1981). The dependent variable was component amplitude. Since the FRN could only be assessed with the feedback condition, the repeated measures ANCOVA for this component omitted the condition variable. Temperament groups were then incorporated as additional between subjects variables for each set of ANCOVAs.

Lastly, Pearson correlations were run to examine relations among the physiological components and the associations between the physiological and the behavioral correlates of response monitoring. Specifically, component amplitude (i.e. ERN, Pe or FRN amplitude on incorrect trials controlling for correct trial amplitude) was assessed in relation to post-error reaction time (calculated as a residual score controlling in order to control for post-correct response reaction time). Separate univariate analyses were run for each component at every region (i.e. sites Fz, Cz, and Pz) controlling for age, gender and temperament across the two conditions.

An additional five children were excluded from the analyses. One participant refused to wear the cap while the other four were excluded due to technical problems during data collection and processing (e.g. too few usable trials due to movement artifact). Thus analyses on the physiological components of response monitoring were run on the remaining 60 participants (27 male, 33 female; mean age = 7.5, *SD* = .70).

Response-monitoring components. The error-related negativity (ERN) was evident in the presence of more negative going waveforms on incorrect as compared to correct trials at both frontal ($F(1,57) = 10.95$, $p < .01$, $\eta_p^2 = .16$) and central sites ($F(1,57) = 4.78$, $p < .05$, $\eta_p^2 = .07$). This pattern corresponds to the source localization literature which identifies a frontocentral generator for the ERN response (Herrmann et al., 2004; van Veen & Carter, 2002) and suggests that children do in fact have the capacity to display the more negative waveforms on incorrect trials (see Figure 11). The ERN was most clearly delineated in individual waveforms rather than the grand-mean waveforms in Figure 11 and several examples are provided in Figure 12.

For the frontal region, the ERN response was moderated by temperament. For shyness there was a two-way Trial Type x Shyness interaction ($F(1,51) = 5.01$, $p < .05$, $\eta_p^2 = .09$). Specifically, children low in shyness exhibited a larger frontal ERN response as compared to children high in shyness ($t(58) = -2.74$, $p < .01$; see Table 4). For inhibitory control, there was a three-way Trial Type x Condition x Inhibitory Control interaction ($F(1,51) = 5.53$, $p < .05$, $\eta_p^2 = .10$) showing that children low in inhibitory control demonstrated a larger ERN response during the no-feedback condition ($t(27) = 5.09$, $p < .01$) whereas children high in inhibitory control displayed a greater frontal ERN response in the feedback condition ($t(31)=2.42$, $p < .05$; see Table 5).

These counter-intuitive results prompted a set of follow-up analyses examining additional characteristics of the temperament groups using the attention focusing and impulsivity scales of the CBQ. Low shy children were found to have significantly greater levels of impulsivity than high shy children ($t(58) = 2.39$, $p < .05$) which may have corresponded to the need for greater recruitment of cognitive control throughout a task. In contrast, children low in inhibitory control had greater problems with attention focusing as compared to children high in inhibitory control ($t(58) = -2.59$, $p < .05$). This finding suggests that stronger engagement of cognitive control may have been especially pertinent to these children in order to maintain their focus in the no-feedback condition.

There were no temperament group differences for the central ERN, however, age did factor into the magnitude of the ERN at site Cz. Specifically, a Trial Type x Condition x Age interaction ($F(1,51) = 5.19$, $p < .05$, $\eta_p^2 = .09$) demonstrated that older participants had a more negative-going ERN response on incorrect trials in the no-feedback as compared to the feedback condition ($t(28) = -2.05$, $p = .05$; see Figure 13).

The error-related positivity (Pe) was present at all three regions (frontal, central, and parietal) with significantly more positive going waveforms on incorrect as compared to correct trials (F's$(1,57) \geq 7.72$, p's $< .01$, $\eta_p^2 = .12, .27, .48$, respectively, see Figure 14). A two-way Trial Type x Condition interaction (F's$(1,57) \geq 5.09$, p's $< .05$, $\eta_p^2 = .08$ and .09, respectively) emerged at both frontal and central sites signifying enhanced Pe responses in the feedback as compared to the no-feedback condition (t's$(59) = -3.00$, p's $< .05$). No interactions emerged for the Pe at the parietal region. Similar to the Pe, the FRN component was present across all three regions with more negative going waveforms on incorrect as compared to correct trials (F's$(1,57) \geq 25.29$, p's $< .05$, $\eta_p^2 =$ .31, .51, .55, respectively, See Figure 15).

Relations between ERPs. Comparison between the ERP components revealed a positive relation between the ERN and Pe across all regions for both the no-feedback (r's $\geq .79$, p's $< .01$) and feedback conditions (r's $\geq .73$, p's $< .01$) such that the smaller the ERN response (i.e. more positive going waveforms), the larger the Pe response. Thus the Pe is maximal when children exhibit a weak ERN response. The magnitude of the Pe also correlated with the magnitude of feedback reactivity at the central and parietal sites (r's $\geq -.46$, p's $< .01$), indicating a similar functional relation between these components across task conditions. Specifically, a larger, more positive-going Pe response was associated with a larger, negative-going, FRN. In contrast, no relation emerged between the ERN and FRN components. Combined, these results highlight the similarities in the developmental time course of the Pe and FRN and further dissociate the functional significance and developmental emergence of the ERN.

<u>ERPs and Behavioral Performance</u>. When controlling for reaction times following correct trials, only the frontal Pe response was associated with post-response reaction time patterns ($F(1,50) = 9.31$, $p < .01$, $\eta_p^2 = .16$) such that the larger the Pe amplitude, the greater the post-error reaction time slowing in the no-feedback condition. In contrast, the frontal and central FRN components were associated with behavioral performance in the feedback condition. Specifically, more negative FRN responses were associated with fewer errors of commission ($F's(1,50) \geq 4.10$, $p's < .05$, $\eta_p^{2'}$ s $\geq .08$). The ERN was not related to behavioral performance in either the no-feedback or feedback condition.

Since the PE and FRN were related to each other but corresponded to different performance outcomes, a post-hoc analysis was conducted to examine whether the divergence in functional significance was associated with a timing effect. To test whether children required a longer time period for response slowing to be effective in altering performance the feedback condition was examined as two separate blocks. A trend emerged in the second block for a positive correlation ($r = -.21$, $p = .09$) between response time and task accuracy such that greater post-error slowing was associated with fewer errors of commission. This pattern demonstrates that children may indeed need a longer period of time to translate performance adjustment strategies, like post-error reaction time slowing, into significant improvements in behavioral performance.

CHAPTER V: DISCUSSION

Overview

The current study was designed to examine the normative patterns of response-monitoring in young children and to determine the effects of performance feedback on behavioral and physiological measures of monitoring. This study also explored variation in response-monitoring as a function of individual differences in temperament style. Children 7.5-years of age were administered feedback and no-feedback conditions of a modified flanker paradigm and behavioral and neural measures of task performance were recorded. Response-monitoring was assessed via a child's response to the commission of an error, a child's responsiveness to feedback, and a child's reaction time slowing following the commission of an error.

Four important findings emerged from this study. First, trial-by-trial feedback significantly influenced children's general task performance in the form of decreased errors of omission, faster reaction times, and the presence of post-error slowing. Second, children generally displayed a more pronounced Pe than ERN response, especially in the presence of feedback. These components were also found to be inversely related to each other. Third, children exhibited a significantly larger neural response to the presentation of negative feedback as evidenced by a larger FRN on error as compared to correct trials. Fourth, both the Pe and FRN components were associated with children's performance adjustment. Specifically, larger Pe responses were positively correlated with greater reaction time slowing following the commission of an error whereas larger FRN responses were negatively correlated with fewer errors of commission. Lastly, exploratory analyses indicate that temperamental differences modulate the physiological components of response-monitoring.

Influence of feedback on task performance

The change in reaction time across conditions suggests that feedback prompted increased task engagement. Initially, the trial-by-trial feedback was anticipated to prompt increased vigilance toward response accuracy; however, the current data suggest that feedback enhanced children's attention to the broader distinction of response/versus no-response as evidenced by the decrease in errors of omission. This pattern of increased reaction time and decreased errors of omission may result from the task instructions and/or an interaction between directions and the developmental difficulty level of the task. More precisely, children were instructed to respond as quickly and as accurately as possible on every trial. However, the flanker task is difficult for this age range since children's ability to execute correct responses in the context of interfering stimuli (i.e. incongruent trials) continues to increases throughout childhood into early adolescence (e.g. Ridderinkhof & van der Molen, 1995). Therefore, the increase in speed during the feedback condition could represent children's adherence to task instructions in the context of a developmentally difficult task.

As anticipated, the presentation of trial-by-trial feedback was also linked to enhanced response-monitoring in the form of post-error reaction time slowing. Specifically, a consistent and significant pattern of reaction time slowing only emerged in the feedback condition. This finding corresponds to earlier work in which children as young as 4-years of age were able to slow their reaction times following errors of commission in a task which provided trial-by-trial performance feedback (Martin

McDermott et al., 2007). Interestingly, neither study found an association between response slowing and performance accuracy. In contrast, the work on response adaptation in adults (Pailing et al., 2002) indicates a clear association between response slowing and accuracy which implies that the full function of children's response slowing may undergo considerable development. The current data further revealed that the different patterns in post-error slowing across the two task conditions were largely driven by reaction time differences on post-correct response trials (see Table 3) with longer reaction times on these trials in the no-feedback as compared to the feedback condition. This pattern may reflect either a high degree of performance uncertainty or alternatively a lack of task engagement following correct trials in the no-feedback condition. Future studies are needed which directly compare response-slowing patterns across children of various ages. Trends in the current data also suggest that children may require the aid of performance feedback in addition to longer periods of time for strategies such as response slowing to be effective in altering performance outcomes. Thus even in the context of feedback, children may require a greater number of task trials to elicit a notable increase in performance accuracy.

Response-locked monitoring components

In addition to post-error slowing, the current study also examined patterns of neural activity linked to response-monitoring. The data show that on average children displayed greater reactivity on incorrect as compared to correct trials for both the ERN and Pe components. The amplitude of the Pe response at both frontal and central sites was enhanced in the feedback as compared to the no-feedback condition. At the central site the magnitude of the ERN and Pe components were jointly influenced by children's age and task condition such that older children displayed a larger ERN in the no-feedback condition but a greater Pe in the feedback condition.

In general, the magnitude of the ERN was stable throughout the task but when accounting for participant age, ERN amplitudes differed across conditions. Specifically, older children displayed a greater ERN response in the no-feedback as compared to the feedback condition whereas younger children did not differ in the magnitude of the ERN across conditions. This somewhat surprising result generates two alternative accounts of the neural activity that registers as the ERN response in children: 1) larger ERNs may represent the enhanced development of the ability to engage in early, pre-conscious error processing similar to the function of the ERN response in adults, or 2) the ERN response in children reflects a signal related to an increased need for greater cognitive control. The latter notion emerges from developmental imaging studies which indicate that the neural networks used to achieve the same processing as adults on specific cognitive tasks involve more regions and more diffuse connections between these regions (Durston & Casey, 2006).

The ERN patterns evident in the current study correspond to prior research examining this component in young children within the context of a flanker paradigm (i.e. Davies et al., 2004). However, work with slightly older children (e.g. 10-year-olds) using the flanker paradigm (Santesso et al., 2005, 2006), as well as studies using basic go/no-go paradigms (Kim et al, 2005; Lewis & Stieben, 2004; Wiersema, van der Meere, & Roeyers, 2007) have found more consistent patterns of ERN expression in children. Likewise, there has been some inconsistency in the literature on the relation between ERN amplitude and performance outcomes. The current study found no associations between ERN amplitude and post-error slowing or overall accuracy rate. These results correspond to the cross-sectional work of Ladouceur and colleagues (2007) which demonstrated that ERN amplitude is linked to accuracy rates in adults but in adolescents.

Overall the full functional significance of the ERN in children remains unclear and the developmental story is further complicated by the continuing debate regarding the function of the ERN in adults. Additional studies are needed which examine the variation of ERN expression within children using multiple paradigms and testing contexts. Although a number of cross-sectional studies in adolescents reveal developmental enhancement of the ERN with age, no such studies have addressed similar patterns across the preschool and early childhood years. Due to the high variability in ERN expression among children, investigations which move beyond the spatial limitations of the ERP methodology may be especially helpful in elucidating the neural regions recruited in children during this early phase of response-monitoring.

In contrast to the variability in children's ERN response, the Pe is traditionally more stable in children (e.g. Davies et al., 2004; Wiersema et al., 2007). Although one study has reported a positive relation between Pe amplitude and children's obsessive-compulsive behaviors (Santesso et al., 2006), differences in Pe amplitude among children is a largely unexplored area of research. As such, this is the first study to identify the influence of feedback on the magnitude of the Pe with larger responses in the feedback as compared to the no-feedback condition. This pattern of enhanced reactivity in the presence of performance feedback supports the view that in addition to conscious error processing, the Pe may also represent the motivational significance of performance outcomes (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005) or some level of affective reactivity linked to performance (Falkenstein, 2004). Both of these functional interpretations are especially pertinent in the current study which examined what has been termed the ‘late’ Pe because this component is localized to a rostal region of the ACC in close proximity to a number of limbic structures (van Veen & Carter, 2002). Therefore, the neural systems underlying conscious error detection in children may well originate in regions strongly associated with affective or motivational processing (Wiersema et al., 2007). Consequently, learning to monitor one’s own performance might begin as a motivationally salient process, developing in concert with more top-down cognitive abilities and eventually falling under the supervision of the prefrontal cortex. As such, external feedback regarding performance may serve a dual function for children as a catalyst to learning in novel scenarios with undefined parameters (i.e. response reversal task) and a means of triggering motivation in paradigms where parameters are well-established (i.e. flanker task).

When examining the relations between the response-locked components, ERN amplitude varied as a function of Pe amplitude such that smaller ERNs were associated with larger Pe responses and vice versa. This reciprocal association may correspond to a transition between conscious and unconscious processing of an error, which is thought to be represented by the Pe and ERN, respectively. Furthermore, in tasks that are difficult for children (i.e. the flanker paradigm), this association between the ERN and Pe components may be more pronounced than in simpler tasks (i.e. go-no/go paradigms) due to different processing requirements. Although the adult source localization literature for the ERN-Pe suggests different neural generators for these components (i.e. Herrmann et al., 2004), a conclusive interpretation of the ERN-Pe association in children is complicated due to the temporal proximity of these components and developmental issues associated with potential changes in neural network orientations due to brain maturation (Marshall, Bar-Haim, & Fox, 2002). Interestingly, the current results also found a relation between Pe amplitude and response-slowing, whereas research in adults has reported associations between response-slowing and both the ERN (e.g. Gehring et al., 1993; Ladouceur et al., 2007) as well as the Pe (Nieuwenhuis et al., 2001). Although it is unknown whether the relation between neural reactivity and response-slowing alters with development, additional studies in children are needed which explore the relation between the ERN and Pe components across ages, in the context of different tasks, in relation to performance outcomes, and at the level of source localization.

Feedback-locked monitoring components

Children demonstrated a clear and well-defined response to the presentation of negative performance feedback in the form of a heightened FRN response on incorrect as compared to correct trials. The predicted relation between ERN amplitude and FRN amplitude was not found, however, an association emerged between the Pe and the FRN. Currently, the reinforcement-learning theory (Hoylroyd & Coles, 2002), is the only theory addressing the generation of the FRN response. Within this framework, the ERN and FRN are conceptualized as closely linked components which vary inversely as a function of learning such that the FRN response propagates back into the ERN response throughout the course of a task (Nieuwenhuis et al., 2004). Furthermore, the majority of studies examining the FRN component have focused on adults and older children using training or gambling paradigms and none of these studies have shown an association between the ERN and FRN in a sample as young as the children in the present study. Indeed, this is one of few studies to demonstrate the presence of a clear FRN response in young children. Moreover, the presence of this component in a paradigm which used relatively mild stimuli (i.e. smiley/frowny faces) as feedback indicates that: 1) children in the current study were motivated to perform the task, and 2) children readily process and use the external monitoring information provided by feedback.

The independence between the ERN and FRN components in the current study may be related to the task design. First, prior FRN studies have used paradigms in which the participants are trained in response mappings as part of the task (i.e. response reversal paradigms) or in which outcomes are uncertain (i.e. gambling tasks) whereas the present study pre-trained participants to response mappings in a flanker paradigm. Second, the RL-ERN theory proposes that the ERN and FRN represent a good/bad evaluation of response choice; however, the flanker paradigm is designed to simultaneously present stimuli that are both mapped to ‘good’ responses (i.e. the flanking stimuli in incongruent trials represent response choices that are considered correct in other trials). As such, the attention allocation required to process the simultaneous presentation of multiple correct choices may hinder the good/bad discrimination. In children, this heavy processing load could contribute to response uncertainty and ultimately, an attenuated ERN. Lastly, the current study assessed the FRN response in a passive format. Specifically, the feedback stimulus was presented chronologically ‘late’ such that the immediate response appraisal had already occurred (i.e. ERN and/or Pe) whereas the feedback stimulus in the previously mentioned paradigms actually triggers the response appraisal process.

In sum, these task discrepancies may have substantially altered the expected relation between the ERN and FRN components. Nonetheless, it is clear that children understood and responded to feedback in the current paradigm. Thus the increased amplitude of the FRN on incorrect trials may reflect a different variation of the good/bad distinction attributed to the ERN/FRN complex of the RL-ERN theory, or alternatively, the FRN in the current task may also reflect children's emotional reactivity to the commission of errors. Since children's learning is strongly linked to motivational factors (Wiersema et al., 2007) it is also plausible that the FRN component in the current study may represent a combination of basic response evaluation and emotional appraisal of performance.

Further support for this proposed dual function of the FRN comes from the relation between the FRN and the Pe response, the latter of which has been characterized as having an affective element. This is the first study to examine the relation between these two components and the results suggest that a common underlying neural system associated with learning and/or affective responding contributes to both the Pe and FRN. Specifically, the magnitude of the Pe response directly corresponded to the FRN response such that larger Pe amplitudes were associated with more negative FRNs.

The current study is also the first to demonstrate an association between the FRN and specific behavioral performance outcomes (i.e. fewer errors). This result suggests that children's processing of errors may need to reach a certain threshold before performance maximizing strategies are implemented. Specifically, trial-by-trial feedback may alter error processing by providing children with a continuing representation of their performance, thus heightening children's self-awareness, increasing the salience of performance outcomes and subsequently increasing performance accuracy. Furthermore, this result may be unique to younger children since work in older children has shown a negative relation between ERN amplitude and errors (e.g. Santesso et al., 2006).

In sum, further research is needed to discern the manner through which feedback assists the correspondence between children's physiological and behavioral monitoring components and whether these associations play a primary role in the developmental transition to adult patterns of response-monitoring.

Response-monitoring in the context of temperament

Lastly, due to the affective element of response-monitoring present in adult studies, individual differences in children's temperamental traits were also hypothesized to correspond to variations in the behavioral and physiological components of children's response-monitoring patterns. For the behavioral measure of response-monitoring, a small number of studies in older children and adults suggest that individual differences in personality can contribute to variations in post-error slowing (i.e. Henderson, 2003) and that these variations can fluctuate over the course of a task (i.e. Luu et al., 2000). In the current study no associations emerged between temperament and reaction time slowing. One explanation for this finding corresponds to the design of the task which may have diminished possible temperament trends in post-error slowing. Although prior studies have presented three or more blocks of trials with feedback, the current study focused on two conditions containing two blocks each of feedback and no-feedback trials. The current data also reveal that performance feedback optimizes the expression of post-error slowing in children which would thereby decrease the chances of this study revealing temperamental differences because children were provided with feedback in only two blocks. Alternatively, the current results may also indicate that previously reported patterns of individual differences in post-error slowing are not overly robust or able to be generalized to different samples. In sum, the present data clearly demonstrate the importance of feedback to children's engagement of post-error slowing in children which highlights the need to consider specific task conditions when exploring individual differences in the use of specific monitoring strategies.

In contrast to the behavioral results, the temperamental dimensions of shyness and inhibitory control both corresponded to specific neural patterns of response-monitoring. Interestingly, these patterns were primarily localized to the frontal region for the ERN component. This regional variation across individuals of different ages or personality traits may result from the frontal region's predisposition to amplify variations in processing due to its protracted period of development. Thus, children may be drawing on increased neural activation in the frontal region to either achieve adequate task performance or to evaluate their task performance. The exploratory data from the present study provide preliminary evidence for differential response-processing in the frontal region for children of different temperaments.

For the ERN, children low in shyness displayed greater frontal reactivity to the commission of errors as compared to children high in shyness. This pattern was in the opposite direction than initially predicted since children high in shyness were expected to show greater reactivity to the commission of an error, especially at the early processing stages. In contrast, the data suggest that low shy children may react more strongly to the commission due to higher impulsiveness and the need for greater effortful control to perform the task. On the contrary, the adult literature suggests that individuals high in trait impulsiveness show a diminished ERN (de Bruijn et al., 2006; Pailing et al., 2002; Stahl & Gibbons, 2007). Thus the current finding in children may result from a non-selected sample in which measures of impulsivity are not extreme enough to correspond to significant deficits in ERN responses. However, this result may also relate to the prior suggestion that the ERN represents a combination of cognitive functions that are not yet solidified in children. Specifically, in low shy children the ERN response to errors may signal the need recruit greater cognitive control to suppress impulsive responding on future trials. This ERN pattern was evident in both the no-feedback and feedback conditions, suggesting that the presentation of feedback did not alter this component of response-monitoring for low shy children.

Similarly, children low in inhibitory control exhibited larger frontal ERN responses than children high in inhibitory control. However, this pattern only occurred in the no-feedback condition which suggests that this group of children may have needed to recruit greater neural resources in response to errors in the absence of external feedback. In contrast, children high in inhibitory control displayed a larger ERN in the feedback condition which signifies that the salience of errors increased for high inhibitory control children in the feedback condition. It is unlikely that these children required additional recruitment of cognitive resources in the context of feedback but it is plausible that these children experienced a heightened emotional or motivational investment in the task in the presence of external feedback which may resulted in the enhanced use of cognitive resources (i.e. a larger ERN response).

This reverse pattern in ERN response between task conditions may correspond to differences in attention focusing between the low and high inhibitory control groups. Low inhibitory control children were rated as having greater difficulty with attention focusing and thus may require stronger recruitment of cognitive control to stay on-task and perform adequately in the absence of external feedback. On the contrary, high inhibitory control children had better ratings of attention control and are theoretically more likely to internalize their performance (Kochanska et al., 1996). Thus, high inhibitory control children would be anticipated to enhance their response-monitoring in contexts in which performance accuracy is highlighted, such as the feedback condition in the current study. Taken in combination, these results further imply subtle differences in the functionality of children's ERN response within the frontal region.

In contrast to the ERN findings, no temperament differences emerged for the Pe and FRN responses. Although these findings mirror the results of the current adult literature, these components are not well studied yet in children and deserve further consideration in both developmental studies as well as studies of individual differences. According to social cognitive models of self-regulation (e.g. Bandura, 1986; Schunk & Zimmerman, 1997; Zimmerman, 2000), regulation is a result of a combination of feedback processes between a person, their behavior and the environment. In this triadic context, feedback loops serve to identify discrepancies between goals and actual performance and proactively enhancing performance goals. Although the current study did not identify individual differences in feedback reactivity, social cognitive models suggest that additional child characteristics beyond temperament, such as competency and performance motivation, may correspond to variation in physiological patterns of response-monitoring. Recent behavioral work on the ‘calibration’ between performance goals, expectations and actual responses to performance feedback (e.g. Winne & Jamieson-Noel, 2002) may also benefit from the addition of psychophysiological measures such as the ERN, Pe and FRN to help elucidate the relations between an individual’s perceptions and actual physiological reactivity. In sum, further investigation is needed in order to determine which individual characteristics distinguish variations in performance reactivity and how these potential differences in reactivity correspond to the utility of performance feedback in young children.

Overall, the variation in the ERN between children of different temperaments signifies that individual differences contribute to variation in the recruitment of particular aspects of cognitive control. Specifically, the counterintuitive findings of enhanced response-monitoring in low shy or low inhibitory control children might represent the need to engage in greater activation of response-monitoring to attain similar levels of task performance as children high in these traits. This interpretation coincides with current notions of a heightened need for cognitive control in atypical populations. For instance, children with certain subtypes of ADHD actually display enhanced ERN responses (Burgio-Murphy et al., 2007). Although the current temperament findings are based on a normative sample rather than a selected sample of extreme temperament groupings, these exploratory findings highlight that two important avenues for future research on the development of children’s response-monitoring are: 1) investigations of the connectivity between neural regions involved in engaging and maintaining response-monitoring, and 2) examination of these connections in the context of individual differences in temperamentally extreme samples of children.

Limitations and future directions

This study sought to examine behavioral and physiological correlates of response-monitoring in children in relation to performance feedback. Therefore, a focused investigational approach was used in which response-monitoring was assessed in the context of one specific selective attention task, the flanker paradigm. The flanker paradigm provides a solid measure of response-monitoring on a cognitive task but it does not encompass all aspects of the broad construct of response-monitoring. As such, additional work is needed to discern the generalizability of the current response-monitoring findings beyond the flanker paradigm to alternative attention tasks. Studies should also attempt to examine response-monitoring patterns across various cognitive and social contexts.

Several limitations to the current study may also be addressed in future research. First, children's response-monitoring was only assessed in one paradigm which is known to be somewhat difficult for children since they consistently perform worse than adults in studies of interference suppression that use tasks like the flanker paradigm (i.e. Ridderinkhof & van der Stelt, 2000; Ridderinkhof, van der Molen, Band & Bashore, 1997; Rueda et al., 2004). Furthermore, task difficultly is especially important to consider in relation to the expression of the ERN component since prior research has linked uncertainty in task performance to diminished ERN amplitudes on incorrect trials and increased amplitudes on correct trials (Bates, Kiehl, Laurens, & Liddle, 2002; Pailing & Segalowtiz, 2004; Schefers & Coles, 2000). Data from studies using easier tasks in which the response outcome is more clearly delineated on a trial-by-trial basis (i.e. go/no-go paradigms) report a stronger expression of the ERN in children (Lewis & Steiben, 2004).

Availability of attentional resources may also be critical to the expression of the ERN in children. In particular, both the neural generator of the ERN, the ACC, and other regions involved in the recruitment of cognitive control, such as dorso-lateral PFC and orbitofrontal cortex, are known to have a protracted course of development throughout childhood. Thus tasks such as the flanker paradigm, which tap multiple regions that are still developing, may correspond to larger variability in ERN expression. As such, comparison of individual monitoring patterns across paradigms that require differing levels of attentional resources or invoke a training/learning component may help clarify the variability in ERN expression within the present study and throughout the current research literature. Alternatively, variation in attentional resources may be varied while maximizing child participation through the use of a single paradigm. For example, a series of 'neutral' trials could be added to the flanker paradigm used in the current study such that the flanking stimuli would not be related to a response (i.e. ** >**). Whether through a single modified paradigm or the use of separate paradigms, future studies should consider accounting for children's confidence level, as well as performance motivation, through either behavioral measures or child report.

A second limitation to the current study was the reliance on parental report of children's temperament. In order to avoid potential biases in parental report, behavioral measures of children's temperament that assess the specific dimensions of shyness and inhibitory control in appropriate contexts (i.e. social interaction in a group or waiting for a prize) could be added. This combined assessment score would provide a more reliable index of temperament which could be used to create more extreme temperament groupings. Future research may also account for individual differences in the fluctuation between ERN and Pe components at several time points throughout development, thus providing a longitudinal context in which to assess the impact of individual differences on response-monitoring patterns.

Lastly, electrophysiological data could be collected using a high density approach (i.e. increase the number of scalp sites) in order to examine the potential regional differences in the activation of response-monitoring. A larger number of sites would also allow for the creation of activation maps that provide a preliminary index of regional activation during processing. Future work may also test the relations between ERP indices of response-monitoring and regional development of cognitive control centers as assessed in fMRI studies.

Conclusions and contributions

The behavioral and physiological indices of response-monitoring in young children were examined in this study. In addition, effects of external feedback and temperament on monitoring patterns were also assessed. Results indicate a substantial positive impact of trial-by-trial feedback on children's task engagement and performance accuracy. Physiological correlates of response monitoring also varied a function of performance feedback with more pronounced physiological reactivity to the commission of errors and to feedback signifying an error. Specifically, larger Pe responses were associated with greater post-error reaction time slowing whereas greater physiological reactivity to feedback in the form of the FRN response was associated with higher accuracy rates. Likewise, error compensation in the form of reaction time slowing after errors was only present in the context of feedback. These findings were further moderated by temperament such that feedback significantly improved task engagement for children low in inhibitory control.

Taken as a whole, these data illustrate the utility of performance feedback for young children in engaging cognitive control processes. More precisely, this is the first study using an ERP paradigm to demonstrate the impact of external monitoring (i.e. the presence of feedback) on child's internal monitoring processes. The current study further contributes to a growing literature on children's error processing which consistently demonstrates an early appearance of the Pe component. However, this study is the only one to present evidence that supports a motivational account of the Pe response among children such that larger Pe amplitudes were evident in the context of feedback.

In sum, the present investigation is unique in the use of multiple assessments of response-monitoring and the focus on monitoring in context. Studies which examine both behavioral and physiological correlates of response-monitoring process are essential to identifying both the manner in which optimal response-monitoring skills are developed and the degree to which these skills can be modulated. In particular, this multi-level approach to examining response-monitoring could significantly contribute to our understanding of the engagement of monitoring processes in relation to children's behavioral and emotional well-being.

Table 1. Participant descriptive data by temperament groupings

Group	n males/females	Age (SD)	Shyness Rating (SD)	Inhibitory Control Rating (SD)
Low Shy/Low IC	18 (9/9)	7.6 (.76)	2.18^{a} (.58)	4.38^{a} (.69)
Low Shy/High IC	18 (8/10)	7.4 (.77)	4.46^{b} (.66)	4.56^{ab} (.69)
High Shy/Low IC	18 (10/8)	7.5 (.79)	2.07^{ab} (.75)	5.86^{b} (.49)
High Shy/High IC	19 (7/12)	7.5 (.58)	4.65^{ab} (.83)	5.82^{ab} (.42)
Total Sample	73 (35/39)	7.5 (.72)	3.36 (1.41)	5.16 (.90)

Note. Temperament ratings with the same superscript differ significantly from each other (*p*'s < 01).

Table 2. Mean behavioral performance on the flanker task by condition

	% Errors Commission (SD)	% Errors Omission (SD)	Reaction Time in milliseconds (SD)
Condition			
No-feedback			
Total Sample	21.0 (11.6)	6.6 (6.5) [a]	686 (124) [b]
Males	21.0 (12.1)	4.3 (4.4)	629 (092) [c]
Females	20.9 (11.3)	8.5 (7.3)	734 (127) [c]
Feedback			
Total Sample	22.8 (11.8)	4.2 (4.4) [a]	653 (120) [b]
Males	21.9 (11.1)	2.7 (3.5)	602 (089) [d]
Females	23.5 (12.6)	5.4 (4.7)	697 (125) [d]

Note. Groups with the same superscript differ significantly from each other (*p*'s < 01).

Table 3. Post-response reaction time (ms)

	Condition	
	No-Feedback (SD)	Feedback (SD)
Trial Type		
After Correct	691 (130) [a]	656 (123) [b]
After Incorrect	679 (133) [a]	670 (136) [b]

Note. Groups with the same superscript differ significantly from each other (*p*’s < 05).

Table 4. Frontal ERN amplitude (uV) by condition and shyness group

	Trial Type	
	Correct	Incorrect
Low Shy	1.25 ^{a}	-0.97 ^{a}
High Shy	0.27	0.57

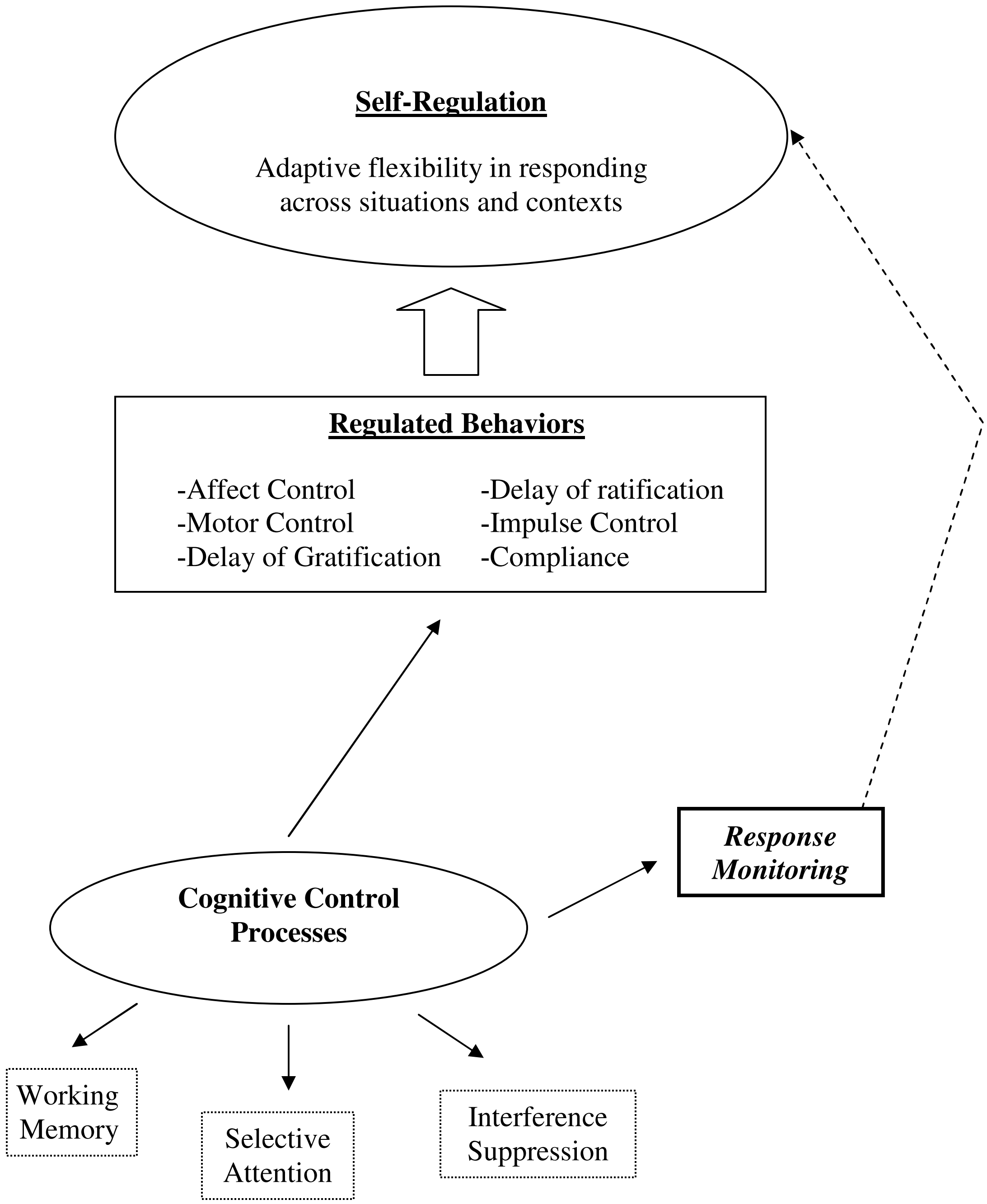
Note. Matching superscripts indicate significant differences (*p*’s < 01).

Table 5. Frontal ERN amplitude (uV) by condition and Inhibitory Control (IC) group

	No-Feedback		Feedback	
	Correct	Incorrect	Correct	Incorrect
Low IC	0.50 ^{a}	-1.32 ^{a}	0.51	-0.65
High IC	1.11	0.50	0.93 ^{b}	-0.83 ^{b}

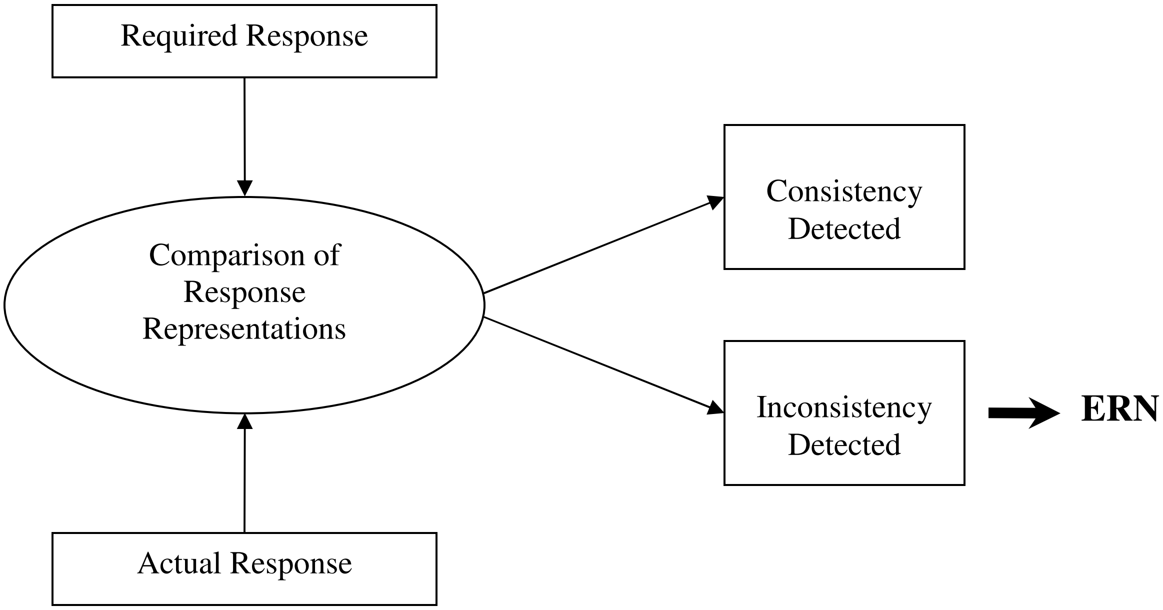
Note. Matching superscripts indicate significant differences (*p*'s < 05).

Figure 1
Basic Model of Link between Response-Monitoring, Cognitive Control and Self-Regulation.



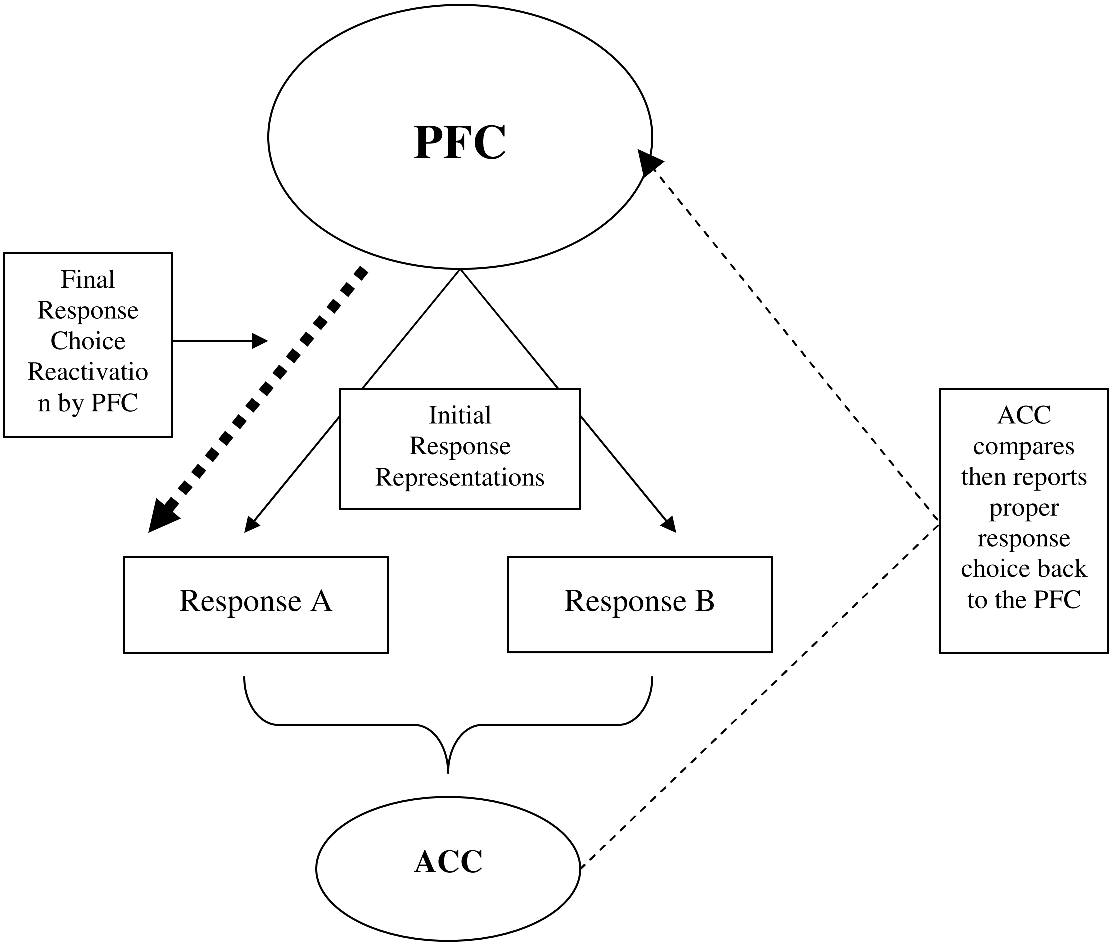
Note: In this model, self-regulation is conceptualized as a broad construct that is accomplished through efficient application of a multitude of cognitive control processes leading to repeated implementation of self-regulated behaviors. The response-monitoring component of cognitive control is viewed as particularly salient to the refinement of self-regulation due to involvement in the activation and maintenance of regulatory behaviors.

Figure 2
<u>Error Detection theory of the ERN.</u>



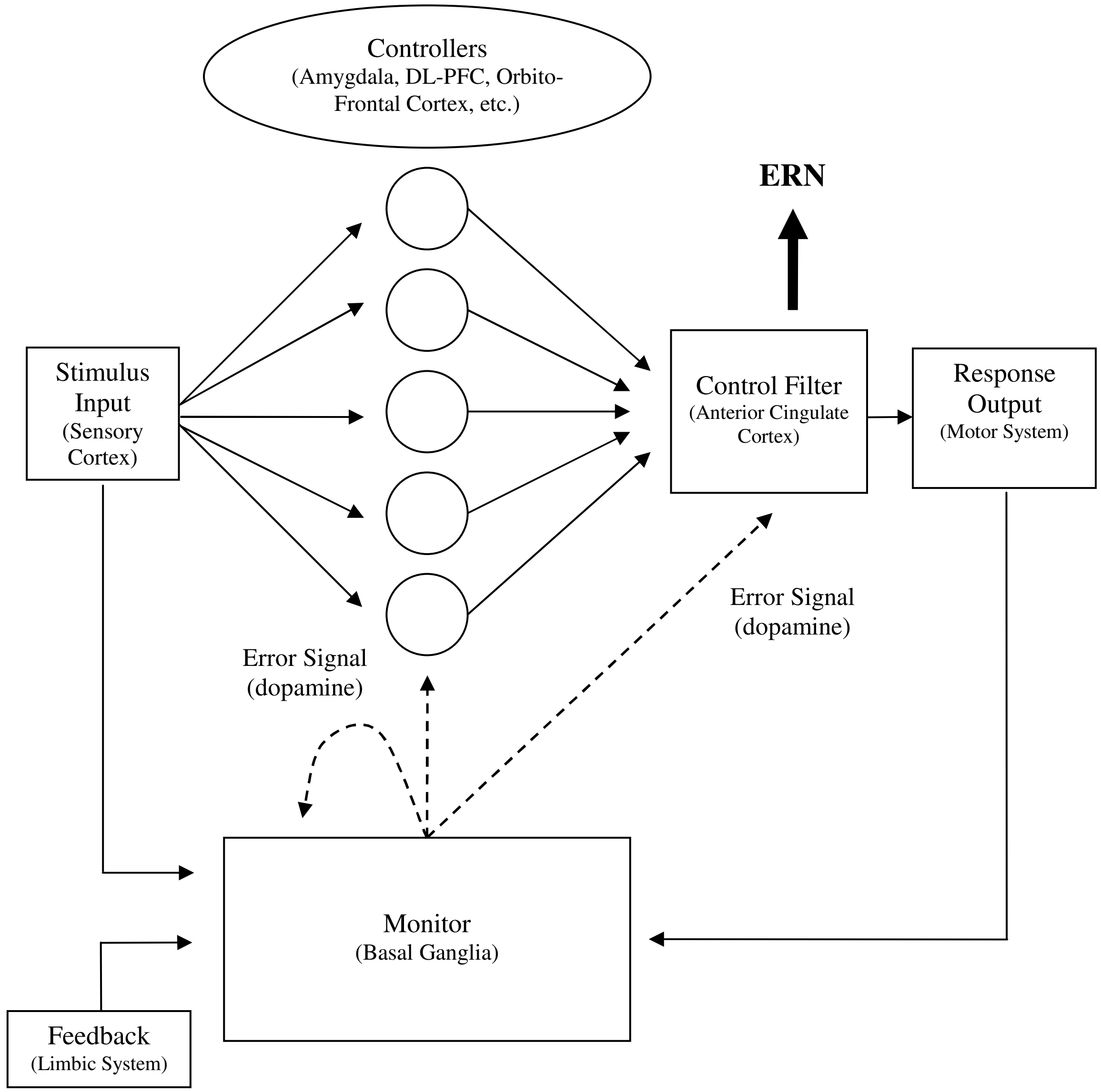
Note. In this model the representation of the actual response is compared to the representation of the intended response. Inconsistency between these representations generates a mismatch, or error signal, in the form of the ERN.

Figure 3
Conflict monitoring theory of the ERN.



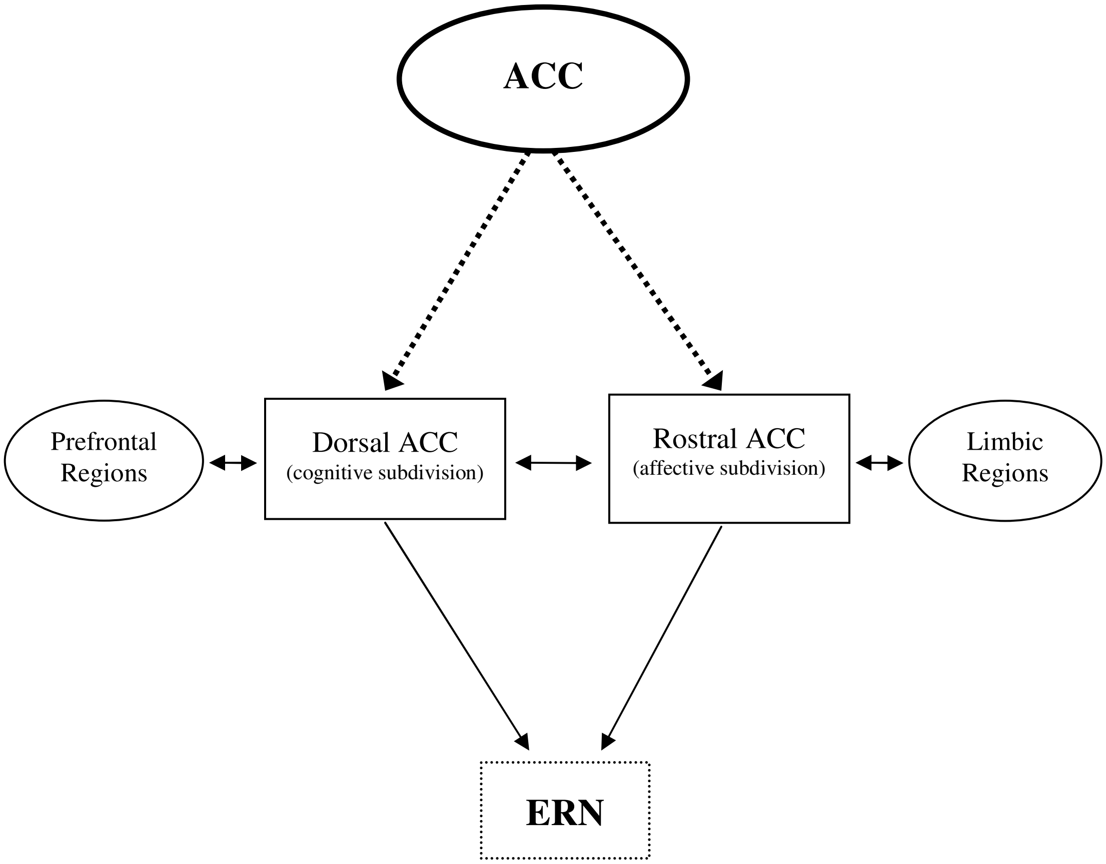
Note. This perspective involves a comparison process and also incorporates the engagement of top-down control. In situations of conflict, the job of the ACC is to determine which response pathway should receive greater activation and relay this information back to the PFC. The PFC is then re-engaged to exert top-down control and more strongly activate the final response choice pathway.

Figure 4
<u>Reinforcement Learning Theory of the ERN.</u> (Figure adapted from Holyrod et al., 2004)



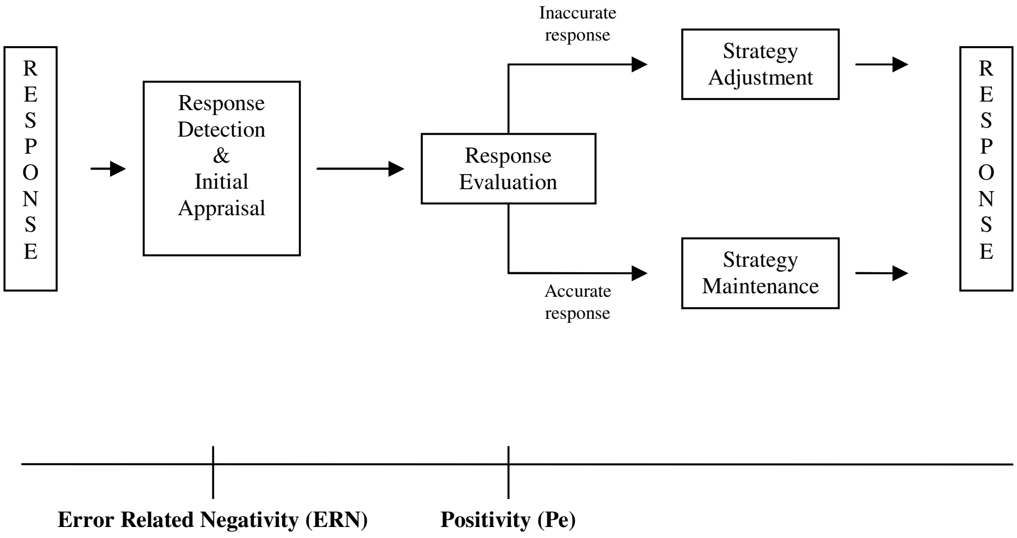
Note. The reinforcement learning theory (RL-Theory) of the ERN portrays multiple systems involved in a continuous loop of response-monitoring. The basal ganglia processes incoming sensory information, predicts outcomes, and also compares these predictions to actual outcomes. When discrepancies are detected, a phasic shift occurs in the dopamine signal which is conveyed to multiple systems, including the ACC which generates the ERN.

Figure 5
Emotional Processing Theory of the ERN.



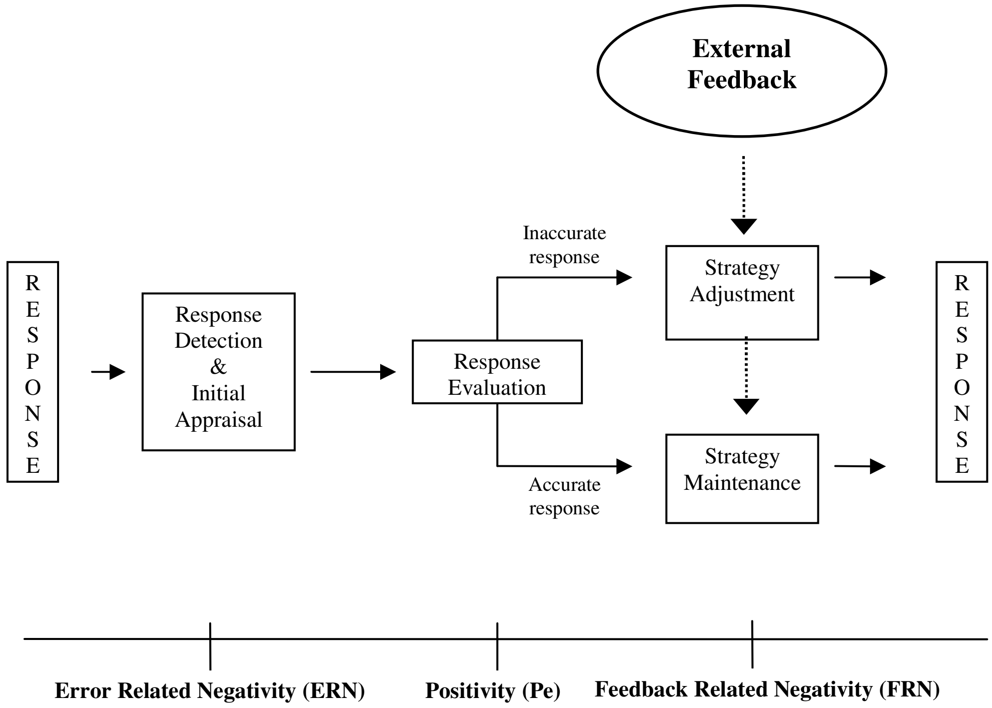
Note. This ERN theory emphasizes that the dual subdivisions of the ACC have connections to both cognitive control regions like the PFC and affective regions of the limbic system. Thus the responsibilities of the ACC include more than just error or conflict detection. In this model, the ACC must determine response patterns, indicate if response expectations have been violated and affectively evaluate the consequences of potential violations.

Figure 6
The Response-Monitoring Mechanism.



Note. The response-monitoring mechanism is composed of various segments that progress in a linear sequence during cognitive processing. The mechanism is activated when a response is detected and initially appraised/processed. An ERP associated with this first step of response-monitoring is called the error-related negativity (ERN). Next the response is evaluated both for accuracy and salience. The emotional impact of the response can be assessed via another ERP call the positivity (Pe). Positive response evaluation leads to strategy maintenance while negative evaluation leads to strategy adjustment.

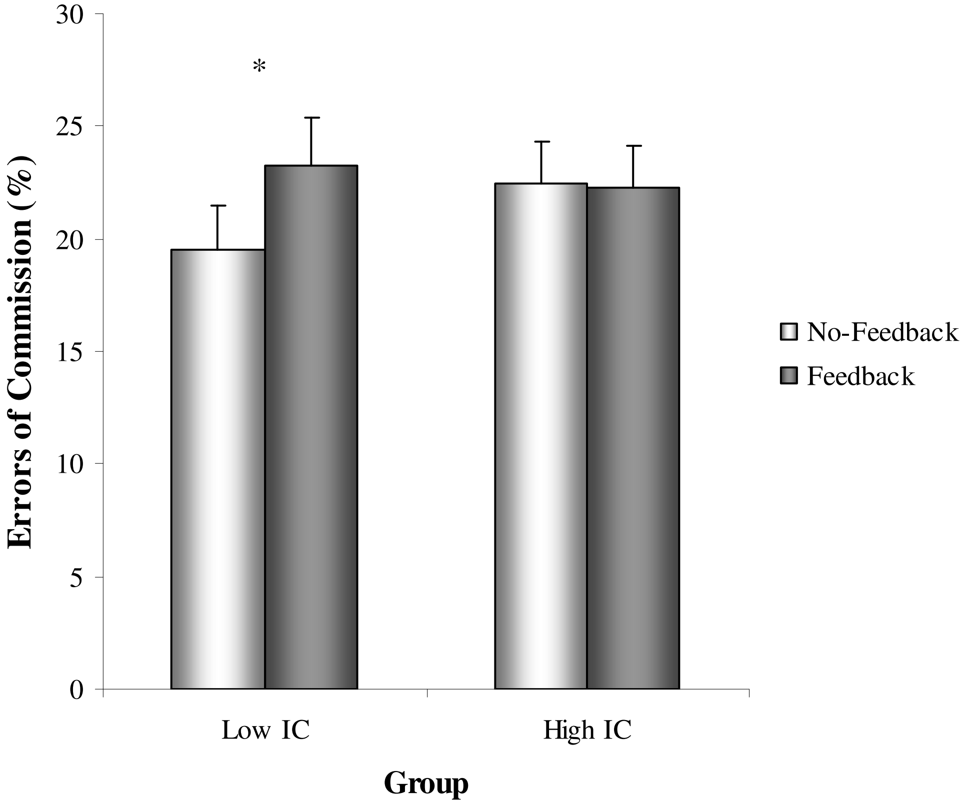
Figure 7
<u>External Feedback and the Response-Monitoring Mechanism.</u>



Note. External feedback is hypothesized to exert influence on response-monitoring at the points of strategy adjustment and strategy maintenance. Subjective reactivity to the presentation of external feedback can be assessed via an ERP called the feedback-related negativity (FRN).

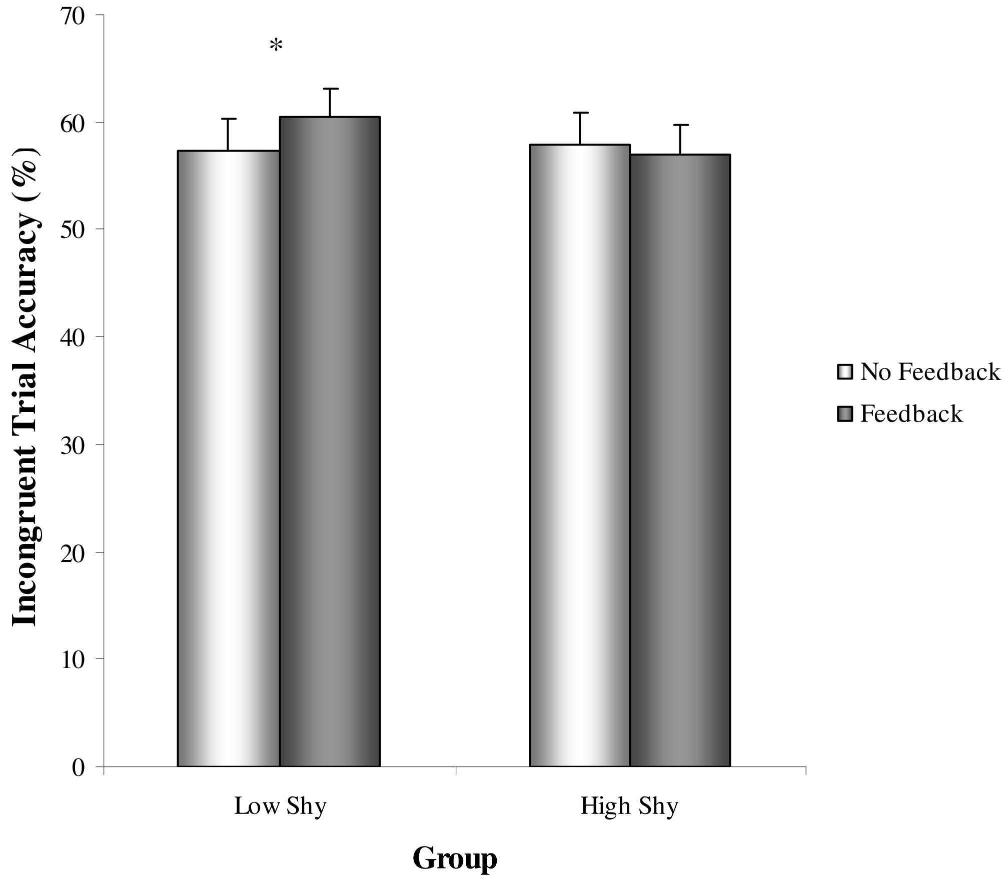
Figure 8

Errors of Commission by Inhibitory Control (IC) and Condition.



Note: * indicates $p < .01$.

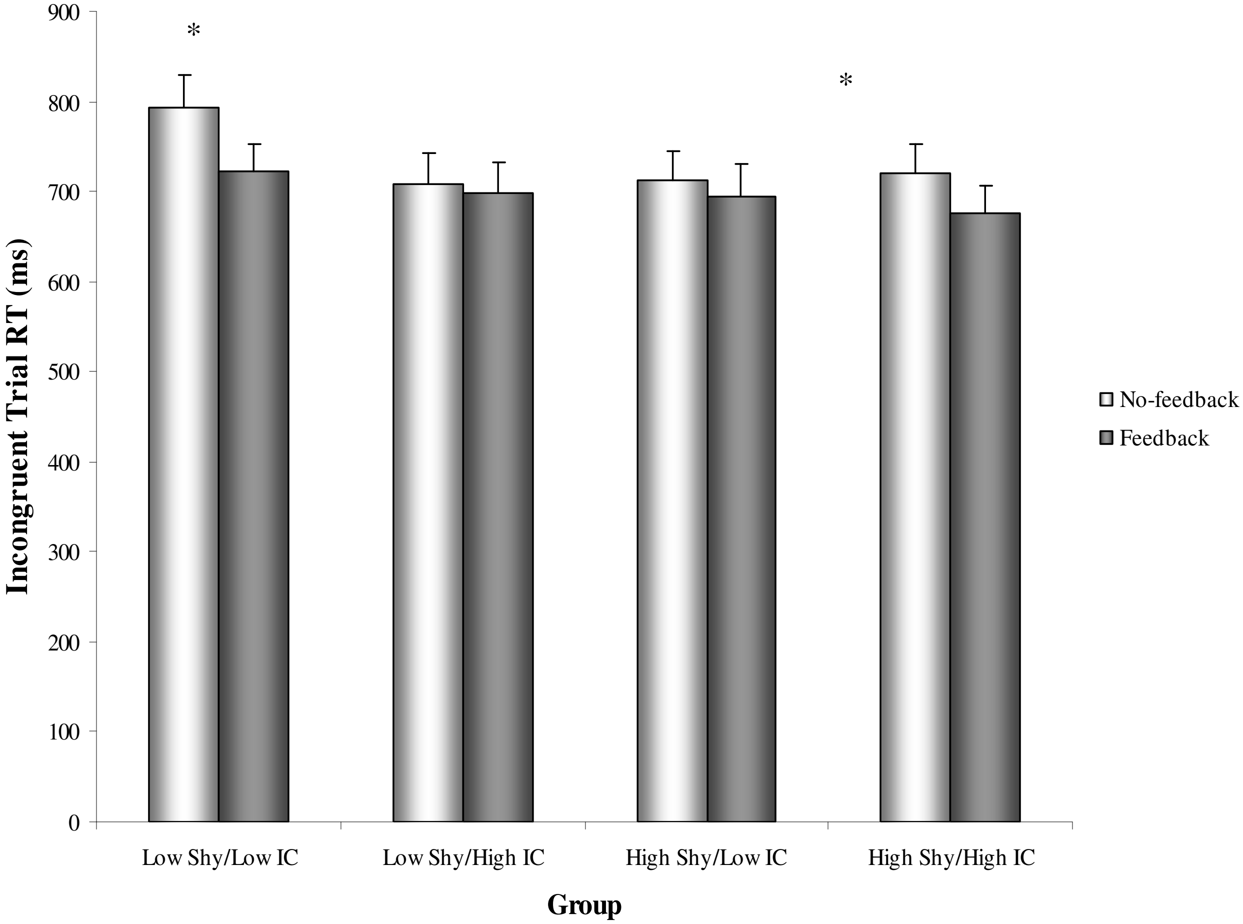
Figure 9
Trial Type Accuracy by Shyness and Condition.



Note: * indicates *p* = .08.

Figure 10

Trial Type Reaction Time by Temperament and Condition.



Note: * indicates $p < .05$.

Figure 11

<u>Response-locked Waveforms by Region for the ERN by condition.</u>

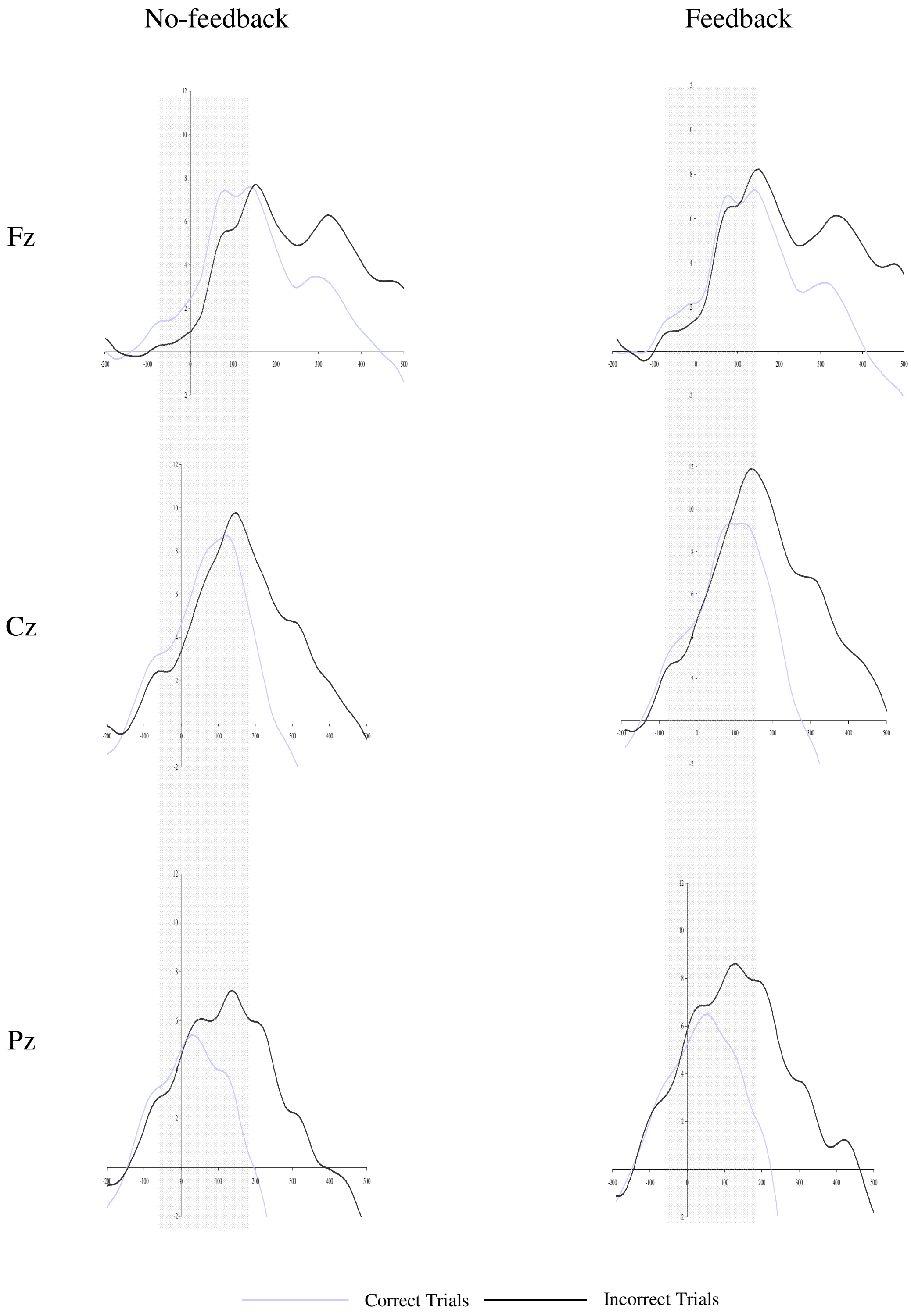


Figure 12

Individual Examples of Response-locked Waveforms for the ERN.

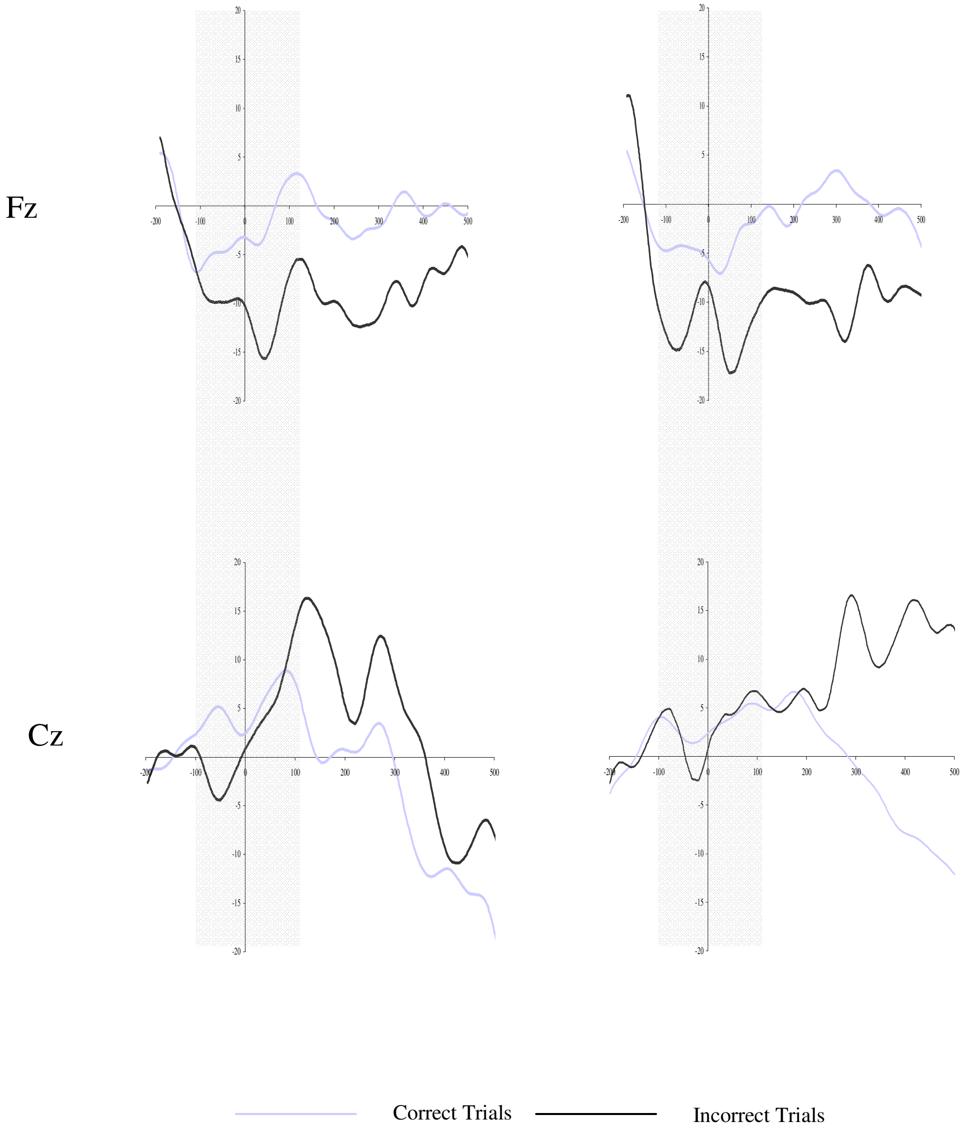
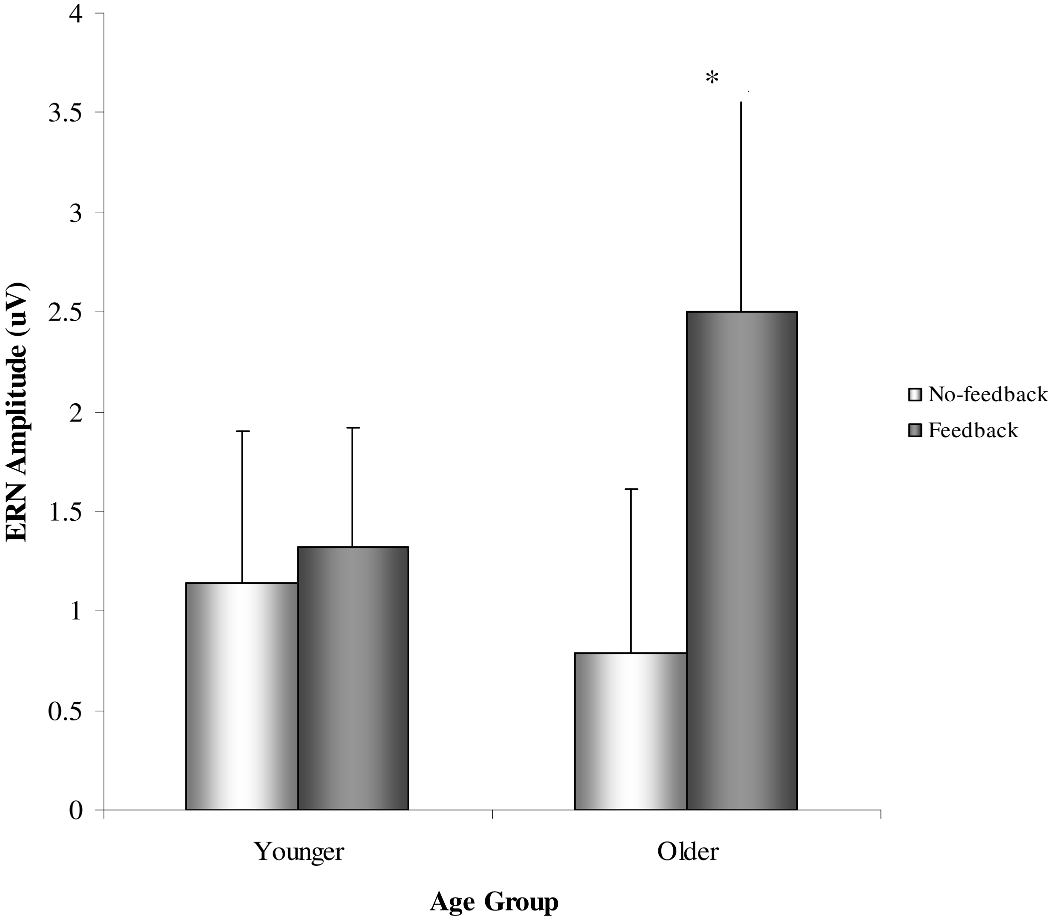


Figure 13
<u>ERN Amplitude by Age.</u>



Note: * indicates *p* = .05.

Figure 14

<u>Response-locked Waveforms by Region for the Pe by condition.</u>

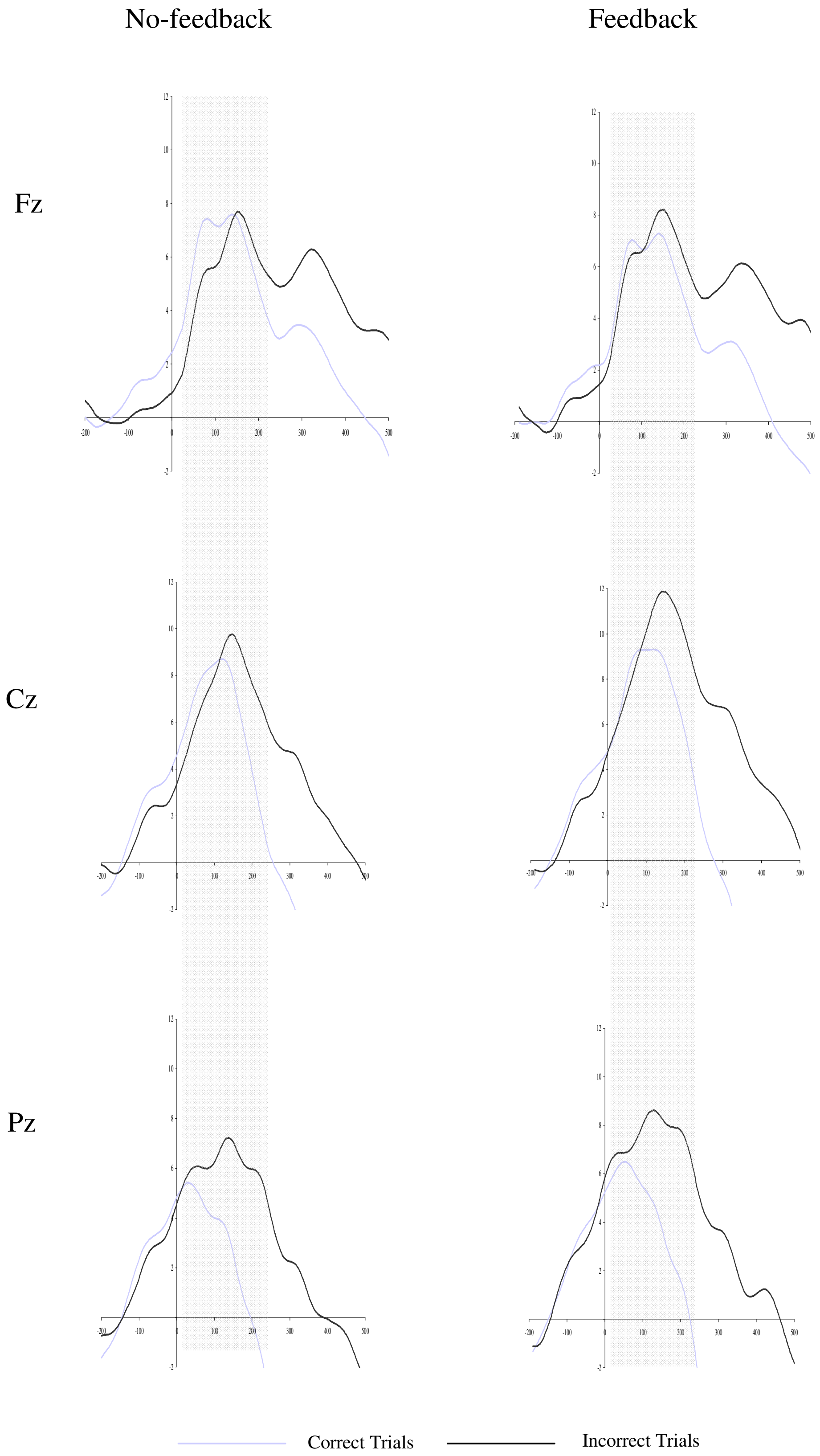
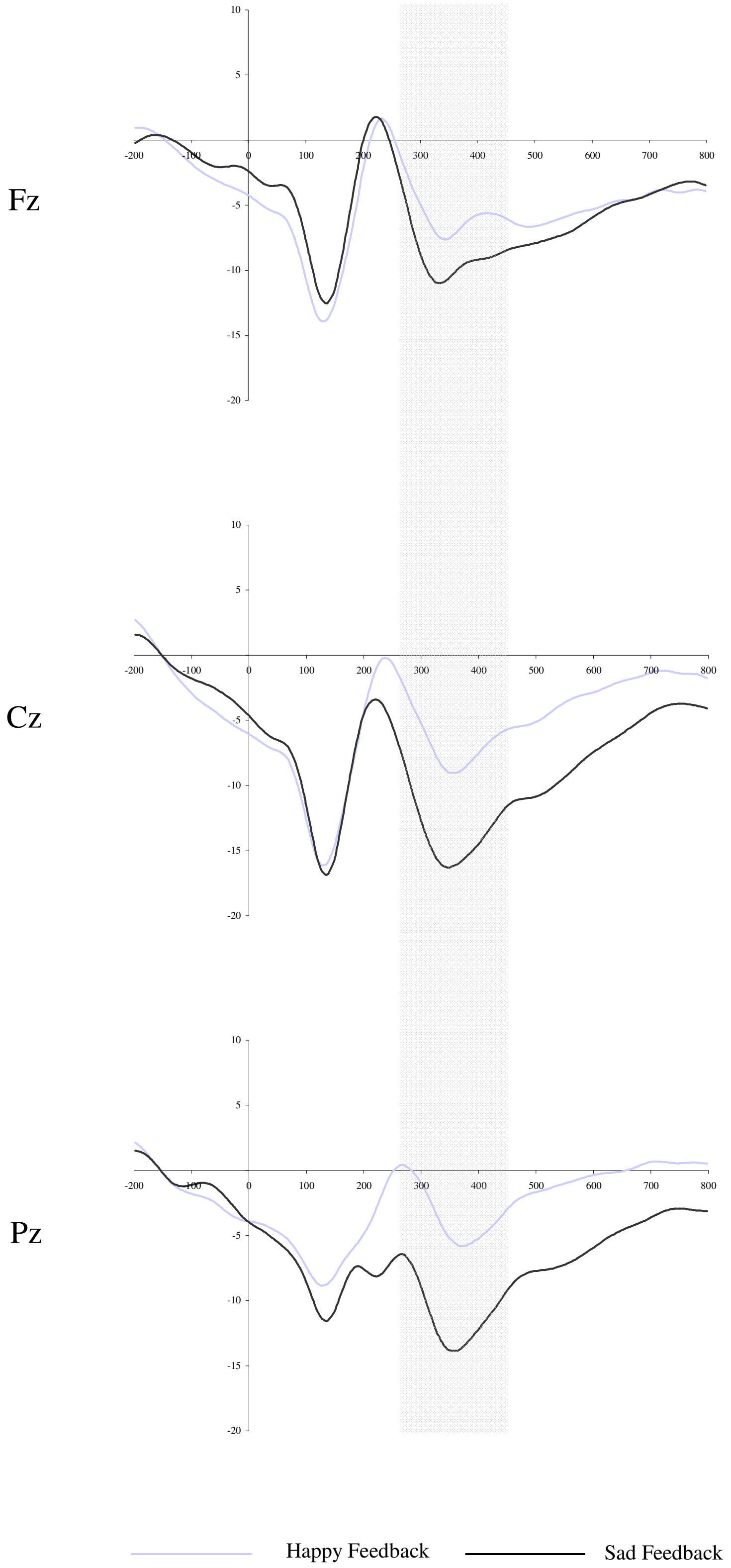


Figure 15

Response-locked Waveforms by Region for the FRN.



Appendix A
Recruitment Letter

Summer 2007

Dear Parents:

Hello! We are writing from the Child Development Laboratory at the University of Maryland to tell you about an exciting study we are conducting. For the past seventeen years, we have been studying the ways in which children develop socially, emotionally, and cognitively, from infancy throughout childhood. Our research has been recognized on television programs such as Dateline, 20/20, and Good Morning America, as well as in *Life* and *USA Today.* These accomplishments have been made possible because of the support from families.

If you have a child, the purpose of this letter is to invite you and your child to participate in our most recent study, in which we are focusing on the development of cognitive processes that contribute to self-regulatory behavior in children. This study is designed to inform us about young children's behaviors in general, and is not designed as an assessment or intervention for individual children.

Upon receiving your completed questionnaire (enclosed), we may contact you by phone to provide you with greater details and to invite you to participate in the study. Families will receive compensation to thank them for their participation in the study. Please note that returning the enclosed questionnaire does not commit you to our project in any way and all information provided will be kept private and confidential – information will not be shared with a third party.

If you have any questions, please feel free to contact us at (301) 405-8249. Our research would not be possible without the invaluable assistance provided by the families that participate in our studies. We appreciate your time, interest, and any information you can provide.

Thank you very much.

Sincerely,

Nathan A. Fox, Ph.D.	Jennifer Martin McDermott, M.S.
Professor	Doctoral Student
Department of Human Development	Department of Human Development

Appendix B

General Information Survey

Child's birth date: _____________

Child's gender: Female ____ Male ____

Child's full name: ____

Child's sibling order: Child is ____ of ____ (ex. 1st of 3)

Was your child born within 2 weeks of her/his due date? Yes ____ No ____

What was your child's method of delivery? Natural ___ Cesarean Section ___ Other ___
If "other", please explain:____

Did you and/or your child experience any birth complications? Yes ____ No ____
If "yes", please explain:____

How many days did your child spend in the hospital after birth?___________________

Has your child experienced any serious illnesses or problems in development since birth?
Yes ____ No ____
If "yes", please explain: ____

Has your child received long-term medication? Yes ____ No ____
If "yes" please explain: ____

May we contact you about our research project? Yes ____ No ____

Parent's name:____
Address: ____
____
Phone: H (   )_______________________ W (   )_______________

Appendix C

Shyness and Inhibitory Control Items from the CBQ

Shyness:

Seems to be at ease with almost any person. (reverse scored)
Is sometimes shy even around people s/he has known a long time.
Sometimes seems nervous when talking to adults s/he has just met.
Acts shy around new people.
Is comfortable asking other children to play. (reverse scored)
Sometimes turns away shyly from new acquaintances.

Inhibitory Control:

Can wait before entering into new activities if s/he is asked to.
Prepares for trips and outings by planning things s/he will need.
Has trouble sitting still when s/he is told to at movies, church, etc. (reverse scored)
Is good at following instructions.
Approaches places s/he has been told are dangerous slowly and cautiously.
Can easily stop an activity when s/he is told “no”.

Appendix D

Flanker Task Instructions

Introduction of Task:

For this game we use directions like 'right' and 'left'.

Can you raise your right hand?

Great! */ (otherwise correct child)*

Can you raise your left hand?

Great! */ (otherwise correct child)*

Okay, in this game you will identify the middle arrow within a row of arrows. When the middle arrow points to the right, you push the right button, and when the middle arrow points to the left, you push the left button. Let's look at some examples.

Sometimes all of the arrows will point in the same direction, like this:

< < < < <

In this row, which direction is the *middle* arrow pointing?

Okay, can you press the ______ button?

**(child can point but ask them to indicate verbally right or left)*

Sometimes all of the arrows will point in the same direction, like this:

> > > > >

In this row, which direction is the *middle* arrow pointing?

Okay, can you press the ______ button?

**(child can point but ask them to indicate verbally right or left)*

Sometimes the arrows will point in different directions, like this:

< < > < <

In this row, which direction is the *middle* arrow pointing?

Okay, can you press the ______ button?

**(child can point but ask them to indicate verbally right or left)*

Sometimes the arrows will point in different directions, like this:

> > < > >

In this row, which direction is the middle arrow pointing?

Okay, can you press the ______ button?

**(child can point but ask them to indicate verbally right or left)*

Before each row of arrows you will see a row of stars on the screen to let you know that the arrows are coming. This is what the stars look like:

* * * * *

You don't have to do anything when you see the stars, the stars just give you a warning that the arrows will be appearing soon.

You want to be as *fast* as you can when pressing the button, *<u>and</u>* you also want to make sure that you are pressing the *correct* button. So remember, press the button that matches the direction of the middle arrow as fast as you can.

<u>*Practice Block*:</u>

So what are you going to do again? *(Press the button that matches the direction of the middle arrow.)*

Right! You want to be as *correct* as and as *fast* as possible.

There will be many trials and we will take several breaks, so just try your best. Are you ready to try a practice round? Great, here we go!

<u>*No-feedback Condition Test Trials*:</u>

Okay, here's the real game. Remember; press the button that matches the direction of the middle arrow. You want to be as *fast* as you can when pressing the button, *<u>and</u>* you also want to make sure that you are pressing the *correct* button. Are you ready? Here we go!

In between blocks congratulate the child for working hard and let them shake out their fingers and blink their eyes. You can ask them if they play any computer games at home or at school, if so, which ones, if not, what else do they like to do? Keep the break short enough to keep attention span but long enough to let them relax (approx. 1 minute).

<u>*Feedback Condition Test Trials:*</u>

Prior to switching blocks (i.e from no-feedback to feedback), take a longer break and also explain to the child what the new blocks will be like. For example,

"You did great on that game! Now we are going to do something just a little different, this time when you press the button you are (or 'are not') going to get feedback - a smiley face or a frowny face to let you know if you pressed the correct button! Just like before you want to press the button that matches the direction of the middle arrow as quickly and as correctly as possible. There will be two blocks and at the end of the second block you get your prize!!! Are you ready to get started?

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