ERROR PROCESSING IN
ATTENTION DEFICIT HYPERACTIVITY DISORDER

by

Shalaine Payne

A thesis submitted in conformity with the requirements
for the degree of Doctor of Philosophy
Graduate Department of Applied Psychology and Human Development
Ontario Institute for Studies in Education
University of Toronto

© Copyright by Shalaine Payne (2016)
Abstract

Performance monitoring refers to the detection of errors and correct responses in ongoing performance and the subsequent cognitive and behavioural adjustment of one’s performance. Adequate performance monitoring is crucial to self-regulation and reinforcement learning, both of which are dysfunctional in attention deficit hyperactivity disorder (ADHD). Although research has shown that children with ADHD adjust less than controls following errors, studies have not determined if this deficit is limited to performance monitoring of errors, termed error processing. One explanation for this deficit is that children with ADHD have a diminished ability to detect errors in their performance, suggesting that the provision of performance feedback would facilitate performance monitoring. Study 1 examined post-error and post-correct adjustment of reaction time in an ADHD and control group using a modified flanker task in two conditions, one with feedback and one without. Study 1 aimed to determine if ADHD participants display a general or specific performance monitoring deficit, and if any deficit could be improved by providing feedback. With feedback, ADHD participants showed similar post-correct adjustment, but significantly less post-error adjustment and accuracy than controls. Feedback significantly enhanced accuracy and post-error adjustment for controls, but not for ADHD participants. Results suggest that the ADHD deficit is specific to error processing and that it does not improve with feedback. Neurological theories and research denote the biological basis of error processing, proposing it as a marker of genetic risk (i.e., an endophenotype) for...
ADHD. Consistent with this hypothesis, Study 2 examined the familiality of error processing in ADHD participants, unaffected siblings of children with ADHD, and controls using the same methodology as Study 1. With feedback, ADHD participants and unaffected siblings displayed similar post-correct adjustment, but significantly less post-error adjustment and accuracy than controls. Notably, unaffected siblings and ADHD participants showed similarly atypical post-error adjustment and accuracy. Results indicate familiality of the error processing deficit in ADHD. Moreover, as post-error adjustment is a behavioral measure that is easily scalable and feasible for large-scale research, error processing as an endophenotype of ADHD is supported. Combined, results promote the inclusion of this deficit in the neurocognitive profile of ADHD.
Acknowledgements

First and foremost, to my husband Dave, I would like to acknowledge your constant and tireless love and support throughout our life together, but especially during these past years of graduate school and thesis research. I have only achieved so much and am pursing my dreams because of your never ending encouragement, strength and optimism. Without your unwavering love and support, none of this would be possible.

To my parents, I would like to acknowledge your love, support, wisdom, guidance, and belief in me throughout my life. Thank you for making me believe that anything I put my mind to is possible and for always setting the bar high and giving me something to reach for.

To Dr. Russell Schachar, I would like to especially acknowledge the generous time and guidance that you have given me in assisting with this thesis and in other endeavors over the past many years. Not only have I learned a tremendous amount from you, but I have also immensely enjoyed working with such an amiable individual. Under your mentorship, you helped me to think and reason like a scientist. I would like to thank you for your confidence in me and my research capabilities and potential.

To my supervisory committee members, Dr. Rhonda Martinussen and the late Dr. Maureen Dennis, thank you for your support and contributions which have helped to shape and refine this dissertation. I would also like to thank my defense committee members, Dr. Judith Wiener, Dr. Paul Sandor, and Dr. Penny Corkum. To the staff of Dr. Schachar’s ADHD lab at SickKids, thank you all for always supporting me and making my time in the lab so enjoyable.

Lastly, but most importantly with respect to my thesis research, I would like to thank all of the children and families who have volunteered to engage in our research, and in doing so have become our partners on the journey to help children with ADHD.
# Table of Contents

1. Chapter 1 - Study 1 Introduction ........................................................................................................... 1  
   1.1 Performance Monitoring .................................................................................................................. 1  
   1.2 Attention Deficit Hyperactivity Disorder and Performance Monitoring ....................................... 8  
   1.3 Study 1 Aims and Hypotheses ..................................................................................................... 11  

2. Chapter 2 - Study 1 Method ................................................................................................................... 17  
   2.1 Participants .................................................................................................................................... 17  
      2.1.1 Inclusion criteria ....................................................................................................................... 19  
      2.1.2 Exclusion criteria ..................................................................................................................... 20  
   2.2 Measures ....................................................................................................................................... 21  
      2.2.1 No Feedback Condition ......................................................................................................... 23  
      2.2.2 Feedback Condition ................................................................................................................. 23  
   2.3 Procedure ...................................................................................................................................... 25  
   2.4 Analyses ........................................................................................................................................ 25  
      2.4.1 Dependent Variables .............................................................................................................. 25  
      2.4.2 Statistics .................................................................................................................................. 26  

3. Chapter 3 - Study 1 Results .................................................................................................................. 27  
   3.1 Sample Characteristics ................................................................................................................... 27  
   3.2 Main and Interaction Effects .......................................................................................................... 29  
   3.3 Correlates of Adjustment .............................................................................................................. 33  
   3.4 Secondary Analyses ...................................................................................................................... 36  

4. Chapter 4 - Study 1 Discussion ............................................................................................................ 38  
   4.1 Possible Influences and Mechanisms of Feedback on Error Processing ..................................... 41  
   4.2 Other Factors that may Influence Adjustment ............................................................................ 45  
   4.3 Educational and Clinical Implications for ADHD ...................................................................... 49  

5. Chapter 5 - Study 2 Introduction ........................................................................................................ 54  
   5.1 Endophenotypes ........................................................................................................................... 54  
   5.2 Sibling Studies of ADHD ............................................................................................................ 55  
   5.3 Endophenotypes of ADHD .......................................................................................................... 57  
   5.4 Error Processing as a Candidate Endophenotype of ADHD ...................................................... 61  
   5.5 Study 2 Aims and Hypotheses .................................................................................................... 64  

6. Chapter 6 - Study 2 Method ................................................................................................................ 66
List of Tables

Table 1 - List of Dependent Variables.................................................................26
Table 2 - Summary of Sample Characteristics for Study 1.................................. 28
Table 3 - Diagnoses in ADHD Sample for Study 1..............................................29
Table 4 - Means and Standard Deviations of Dependent Variables.........................31
Table 5 - Univariate ANOVA Post-Hoc Results..................................................31
Table 6 - Correlates of Adjustment in Study 1................................................... 35
Table 7 - Summary of Sample Characteristics for Study 2.................................73
Table 8 - Diagnoses in ADHD and Unaffected Sibling Samples for Study 2.........74
Table 9 - Means and Standard Deviations of Dependent Variables.......................76
Table 10 - Univariate ANOVA Post-Hoc Results...............................................76
Table 11 - Correlates of Adjustment in Study 2.................................................80
List of Figures

Figure 1 - Representation of a trial from the modified flanker task................................. 24
Figure 2 - Post-correct adjustment in milliseconds (ms) in Study 1................................. 32
Figure 3 - Post-error adjustment in milliseconds (ms) in Study 1................................... 32
Figure 4 - Accuracy (percent correct) in Study 1............................................................ 33
Figure 5 - Post-correct adjustment in milliseconds (ms) in Study 2................................. 77
Figure 6 - Post-error adjustment in milliseconds (ms) in Study 2................................... 77
Figure 7 - Accuracy (percent correct) in Study 2............................................................ 78
List of Appendices

Appendix A - DSM-IV-TR criteria for Attention Deficit Hyperactivity Disorder................119
1. Chapter 1 - Study 1 Introduction

1.1 Performance Monitoring

Self-regulated behavior and learning that is goal-directed requires continuous monitoring of ongoing performance in order to detect and eliminate errors. Performance monitoring is an executive control process that is central to the regulation of elementary mental operations and is a critical component for any feedback learning system (Logan, 1985; Norman & Shallice, 1986). Performance monitoring refers to surveying one’s behaviour for errors and correct responses, detecting errors and correct responses, and the subsequent adjustment of performance in response to those errors or correct responses. While correct answers are in line with successful goal achievement, errors indicate deviation from an originally intended action and hinder the achievement of a particular goal for an individual. In fact, skill acquisition has been described as the successive elimination of errors (Ohlsson, 1996). Performance monitoring that specifically involves detecting errors and adjusting one’s behavior in response to those errors is often referred to as error processing; whereas the term performance monitoring reflects detecting and adjusting to both errors and correct responses (Albrecht et al., 2008; B. Albrecht et al., 2009; Endrass, Klawohn, Schuster, & Kathmann, 2008; O'Connell et al., 2009).

Research examining the functioning of the performance monitoring system began several decades ago with behaviourial studies investigating healthy controls’ responses during speeded choice reaction time tasks (Rabbitt, 1966). Specifically, early studies discovered that when individuals performed a task quickly they tended to slow their reaction times on trials following an error (Rabbitt, 1966). Rabbitt (2002) also demonstrated that despite instructing young adults to ignore errors in their performance, they continued to register them as their reaction times following errors tended to be slow relative to their reaction times following correct responses.
This result is consistent with the notion that individuals adjust their speed in response to an error (Rabbitt & Rodgers, 1977; Laming, 1979).

On tasks in which either accuracy, speed, or both are emphasized, the appropriate form of adjustment is to slow one’s reaction time following the commission of an error, in order to reduce the likelihood of committing future errors (Rabbitt, 1966). Employing slowing strategies on reaction time tasks has been found to be adaptive in that the slower response speed increases the likelihood of making a correct response on subsequent trials, thereby reducing the number of errors made. Slowing after correct responses has also been found on some tasks with healthy young adults (Castellar, Kühn, Fias, & Notebaert, 2010; Verbruggen & Logan, 2009). However, individuals slow more on tasks after making errors than correct responses, suggesting a strategic adjustment to reduce errors. Post-error slowing in particular has been found on a variety of cognitive tasks (Gebring & Fencsik, 2001; Botvinick et al., 2001), including those that require inhibiting a response rather than executing one (Schachar et al., 2004). The post-error adjustment revealed across these tasks is postulated to be a behavioural index of the functioning of the performance monitoring system.

To enable detection and any subsequent adjustment, ongoing cognitive processes designed to monitor one’s performance must take place (Yordanova, Falkenstein, Hobnsbein, & Kolev, 2004). Gehring and colleagues (1993) suggest that it is plausible to assume that the prevalence of errors and associated high costs have led to the evolution of cognitive mechanisms aimed at monitoring the accuracy of one’s actions, and those that attempt to correct or compensate for errors (Gehring, Gross, Coles, Meyers, & Donchin, 1993). The notion that a performance monitoring system exists is evident in many theories of cognition. For example, the concept of performance monitoring is included in theories of action (MacKay, 1987), learning
of most relevance to ADHD, in theories of executive control systems (Logan, 1985; Shallice, 1988). Although it is clear that individuals show performance monitoring, the specific mechanisms underlying this process are currently being investigated and have been considered in several neural and psychological theories.

Holroyd and Coles (2002) proposed a neural theory that links performance monitoring to reinforcement learning. They note that both performance monitoring and reinforcement learning evaluate ongoing events to support the neural development and behavioural expression of adaptive behaviors. Holroyd and Coles (2002) propose that when the neural system first detects that the consequences of an action are worse than expected, for example when one commits an error, a negative prediction reinforcement learning signal, also known as a negative prediction error is created (see Schultz, 2006). This neural signal is then conveyed to the anterior cingulate cortex (ACC) via the mesencephalic dopamine system (Debener et al., 2005; Gehring, Liu, Orr, & Carp, 2011). The neural signal is then used by the ACC to train the motor system in a way that is consistent with reinforcement learning principles and initiates the reallocation of prefrontal resources based on changing conditions via altered plasticity (i.e., this leads to behavioural adjustment on reaction-time tasks). Holroyd and Coles (2002) provide experimental evidence that is consistent with their theory that a neural signal is elicited by the dopaminergic system responsible for reinforcement learning. Additional research indicates that the dorsal ACC can be viewed as a task-set controller, meaning that it has explicit awareness of a cognitive task-set, and then uses this information to update other brain structures as needed and influence implicit and reinforcement learning through its dopaminergic projections (Bhaijiwala, Chevrier, & Schachar, 2014). Adjustment also seems to invoke widespread neural mechanisms involved.
in updating working memory and adjusting the motor system through influences on the striatum (Chevrier & Schachar, 2010). Therefore, it is likely that the extent of adjustment (i.e., the task modification once reinforcement learning takes place), is initiated by the neural detection of an error or correct response and is further dependent on dopaminergic pathways and mechanisms.

Theories drawn from cognitive psychology suggest that slowing following an error results from the comparison of actual responses with representations of intended responses (Bernstein et al., 1995; Dehaene, Posner, & Tucker, 1994; Holroyd & Coles, 2002). These comparator theories posit that post-error adjustment indicates that representations of recently executed responses are stored in short-term memory (i.e., memory that holds information in an active, readily available state for a short period of time), and are compared with the instruction set for a given task which is held in working memory (i.e., memory that can hold, process, and integrate both new and already-stored information) (Gebring et al., 1993; Scheffers et al., 1996; Scheffers & Coles, 2000). This comparison takes time and delays an individual’s response on subsequent trials if there was an error that required response adjustment. However, this process of comparison would take less time after a correct response, suggesting post-correct adjustments would not be as great as post-error adjustments.

Another cognitive theory of performance monitoring suggests that slowing of responses following errors reflects an attempt to correct the erroneous response immediately after it is made (Dehaene et al., 1994; Rabbitt & Rodgers, 1977). As performance monitoring is intimately linked with learning (Tam, Maddox, & Huang-Pollock, 2013; Ullsperger, 2010a), it is possible that participants are increasing the amount of time they take in choosing and executing a response following an error to decrease the probability of future errors occurring, reflecting intention of the sort associated with the very idea of executive control.
A more recent analysis explicitly tested psychological theories of adjustment by fitting a “drift diffusion model” to data on a lexical decision task (Dutilh et al., 2012). The study examined the effects of task errors on the latent psychological processes hypothesized to explain post-error adjustments. The authors found that post-error adjustment was associated with an increase in response caution and a change in response bias; that is, participants’ took their time to respond because they were more hesitant and cautious, and changed their typical patterns of responding by adapting a more successful response strategy (Dutilh et al., 2012). Evidence did not suggest that post-error adjustment was caused by perceptual distraction or time wasted on irrelevant processes, supporting a performance monitoring account of post-error adjustment.

Another study investigated how post-error adjustment was linked to outcome expectations (Castellar et al., 2010). Healthy young adults completed a four-choice reaction time task in two conditions that manipulated outcome expectancy, one condition where participants’ were more likely to be correct (achieving 75% accuracy), and another where they were more likely to be incorrect (achieving 35% accuracy). Results indicated that post-error slowing was evident in the 75% accuracy condition where errors were unexpected, but post-correct slowing was observed in the 35% accuracy condition where correct responses were unexpected. The authors conclude that a discrepancy between outcome expectancy and actual performance is important for cognitive and behavioural adjustments to occur (Castellar et al., 2010).

A cognitive and behavioural model of performance monitoring that has been frequently suggested in previous research is the bi-phasic model of performance monitoring (Shiels, Tamm, & Epstein, 2012). This model of performance monitoring involves both detection (i.e., detecting errors or correct responses), and subsequent adjustment of performance. Therefore, detection processes serve as an antecedent to adjustment processes. These processes are thought to be
distinct as shown in the example of making an error: A person may possess the knowledge of whether a response is incorrect (i.e., detect the error), but lack or have difficulty implementing the knowledge or strategies that are required to perform better on subsequent trials (i.e., correct the error; Ohlsson, 1996). Alternatively, an individual may not be aware that they have made an error (i.e., detect the error), but when it is brought to their attention, they may have the knowledge and/or skills required to rectify the error.

Physiological studies lend support to the bi-phasic model of performance monitoring and have been able to separate detection from adjustment processes. Neuroimaging research on error detection reveals activity in bottom-up pathways from the midbrain to the basal ganglia (striatum) to the midline pre-frontal cortex, all of which are highly dopaminergic (Chevrier & Schachar, 2010). The dopaminergic system (synthesis, function or metabolism) is implicated in neurodevelopmental disorders such as ADHD as will be described below. In contrast to the neural mechanisms of detection, adjustment evokes widespread brain activity involved in updating working memory and adjusting the motor system through influences on the striatum (Chevrier & Schachar, 2010). Neuroimaging studies have helped to distinguish the component processes of performance monitoring because they activate distinct neural circuits, even though they are intimately related and correlated (Bhaijiwala, Chevrier, & Schachar, 2014; Chevrier & Schachar, 2010; Schultz, 2006).

Similarly, electrophysiological (ERP) research generally supports a bi-phasic model of performance monitoring by proposing that there are observable neural correlates of both the detection and adjustment phases. Most of the ERP evidence for detection arises from studies that have observed a specific brain wave that is generated after errors are made, termed the error-related negativity (ERN), and when correct responses are made, termed the correct-related
negativity (CRN) (Falkenstein, Hobnsbein, Hoormann, & Blanke, 1991; Gehring et al., 1993; Ullsperger & von Cramon, 2004). The ERN and CRN respectively are believed to represent the cognitive processes that are engaged by errors and correct responses. There is far more research on the ERN than on the CRN given the consistency with which the ERN has been found on error trials, leading to it be conceptualized as an ERP index of cognitive error detection (Bernstein, Scheffers, & Coles, 1995; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Holroyd, Dien, & Coles, 1998; Hughes & Yeung, 2011; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). In fact, studies have found that the ERN also arises when external feedback about the accuracy of a response is provided (Luu, Tucker, Derryberry, Reed & Poulsen, 2003; Miltner, Braun, & Coles, 1997). The generation of the ERN also occurs during several different tasks, including the Eriksen Flanker task, the Sternberg Memory Scanning task, as well as several auditory and visual focused and divided attention tasks (for a review see Falkenstein et al., 1995; Gehring, Coles, Meyer, & Donchin, 1995). It is also found when errors are committed across motor modalities of the feet, eyes, and hands (Holroyd et al., 1998; Nieuwenhuis et al., 2001).

Despite these findings regarding the ERN, evidence also shows that the ERN is often correlated with the magnitude of adjustment leading to some uncertainty regarding whether the ERN reflects error detection and/or adjustment (Falkenstein et al., 1990; Vidal et al., 2000). Although there is uncertainty about what process the ERN actually reflects, another ERP index, the error positivity, or Pe, also relates frequently to the degree of adjustment. As a result, Pe is often thought to be related to the evaluation of an error and/or adjustment following error detection (Falkenstein et al., 2000; Leuthold & Sommer, 1999; Overbeek, Nieuwenhuis, Ridderinkhof, 2005; Nieuwenhuis et al., 2001; Hajcak, McDonald, & Simons, 2003; Luu, Collins, & Tucker, 2000). The Pe is a positive wave that usually follows the ERN after an
erroneous response (Ullsperger & von Cramon, 2004). The presence of a Pe-like wave on correct trials (termed Pc) has varied across studies, limiting the investigation of this waveform. However, when Pc was found, it had much smaller amplitude than Pe (Nieuwenhuis et al., 2001; Falkenstein et al., 1990). The hypothesis that Pe is related to the evaluation of an error and/or adjustment is supported by a study that reported that the Pe was only observed after errors (Vidal, Hasbrouco, Grapperon, & Bonnet; 2000), and by other studies that have found that Pe was only present for errors that participants were consciously aware of (Hughes & Yeung, 2011; Nieuwenhuis et al., 2001).

While ERP research provides support for the bi-phasic model of performance monitoring, there is considerable variability among studies with regards to what cognitive or behavioural process(es) are actually represented by the ERP indices found. There are also significant limitations to the technical and often difficult real-world application and use of such physiological measures, especially when compared to behavioural measures. The limited number of studies employing behavioural measures to assess performance monitoring strongly points to the need for such research. Behavioural measures of performance monitoring have the advantage of feasibility and scalability over physiological metrics, and therefore can be more useful from both a clinical and educational perspective to studies of disorders like attention deficit hyperactivity disorder (ADHD).

1.2 Attention Deficit Hyperactivity Disorder and Performance Monitoring

ADHD is a common psychiatric disorder of childhood that affects approximately 5% of children across cultures (American Psychiatric Association, 2013). ADHD is characterized by chronic levels of inattention, impulsiveness and hyperactivity, or both. Atypical development
compromises daily functioning in important areas of life including academic performance, and peer and family relationships (Smith, Barkley, & Shapiro, 2006). ADHD is also associated with considerable impairment across multiple domains of functioning. Children with ADHD consistently display poor emotional self-regulation and behavioural judgment, and are at increased risk for the development of substance use, academic underachievement and school failure, low occupational status, difficulties with social relationships, and overall poor social adaptation (Smith et al., 2006).

These learning, social, and behavioural problems all suggest that individuals with ADHD have some degree of difficulty with their executive functioning. Executive functions exert cognitive control on processes that enable efficient planning, execution of responses, and regulation of goal-directed behaviour (Mesulam, 2002). Examples of situations in which executive functioning is required include inhibiting one’s behaviour, mentally holding and manipulating information, and behavioural and emotional self-regulation and self-monitoring. A widely held theory of ADHD postulates that core symptoms of the disorder arise from atypical executive functioning (Barkley, 1997; Pennington & Ozonoff, 1996). According to this theory children with ADHD exhibit deficits in a variety of cognitive processes that fall under the umbrella of executive functions including response to reward (Douglas & Parry, 1994, 1983; Solanto et al., 2001; Sonuga-Barke, 2003), response inhibition (Schachar et al., Mota, Logan, Tannock, & Klim, 2000; Barkley, 1997), and working memory (Barnett et al., 2001).

Some researchers place performance monitoring at the very top of an executive function deficit hierarchy in ADHD because it is believed that performance monitoring is critical to any ongoing and future goal-directed behaviour (van Meel et al., 2007). Evidence of a performance monitoring deficit in individuals with ADHD is suggested by symptoms of poor self-regulation,
altered reinforcement learning, failure to learn from mistakes, and importantly the role the
dopaminergic system plays in both ADHD and performance monitoring. While few studies have
examined performance monitoring in children with ADHD, when using post-error adjustment as
an index of performance monitoring, evidence of a deficit in children with ADHD is consistent
(Groen et al., 2008; Jonkman et al., 2007; Wiersema, van der Meere, & Roeyers, 2005; Krusch et
al., 1996; Schachar et al., 2004; Sergeant & van der Meere, 1988). For example, Schachar et al.
(2004) found that children with ADHD slow significantly less in their reaction times following
errors of failed inhibition compared to controls. This difference in post-error adjustment could
not be attributed to group differences in IQ, age, or gender. Another study used ERP techniques
to compare children with ADHD to typically developing children on a feedback-based learning
task (Groen et al., 2008). The ADHD group showed a decreased ERN and Pe throughout the
task. A study that also employed ERP methodology compared children with ADHD to typically
developing children on their performance of a speeded choice reaction time task (Jonkman et al.,
2007). Children with ADHD made more errors, especially in high-response-conflict conditions,
and did not show appropriate post-error adjustment. Some researchers have also observed
diminished error detection and correct detection ERP indices in individuals with ADHD to
compared to controls (Samyn, Wiersema, Bijttebier, & Roeyers, 2014; van Meel, Heslenfeld,
Oosterlaan, & Sergeant, 2007).

While the results generated by these studies confirm a deficit in performance monitoring
in children with ADHD, there has been little research on understanding how these deficits may
be attenuated. One study reported that stimulant medication in children with ADHD increased
post-error adjustment and accuracy on a Sternberg task (Krusch, et al., 1996). To date, other
than studies using stimulant medication, there have been no studies of behavioural manipulations
of performance monitoring in children with ADHD. Such research is crucially important to the development of cognitive and behavioural interventions aimed at improving this deficit. Study 1 of my thesis aims to address this significant gap in the research on performance monitoring in children with ADHD. It has been argued that children with ADHD are often not aware of their performance, and particularly their errors. In fact, previous research has shown that children with ADHD tend to overestimate their competencies (Owens, Goldfine, Evangelista, Hoza, & Kaiser, 2007). This has been called the positive illusionary bias and describes the discrepancy between children with ADHD’s self-reported competence and actual competence. Children with ADHD exhibit notably greater self-reported competence compared to their actual competence, and compared to parent and teacher ratings of their competence (Hoza, Gerdes, Hinshaw, Arnold, Pelham, et al., 2004). Similarly, the self-predicted and actual performance of children with ADHD on academic and social tasks is also prone to the positive illusionary bias (Hoza, Pelham, Waschbusch, Kipp, & Owens, 2001; Ohan & Johnston, 2011). Research has also shown that children with ADHD show the positive illusionary bias when self-reporting their ADHD symptoms compared to parent reports of their symptoms (Wiener, Malone, Varma, Markel, Biondic, et al., 2012). The notion that children with ADHD overestimate their competencies and underestimate their symptoms, suggests that they may have difficulty with accurate self-performance knowledge and the ability to detect errors in their performance. This difficulty may in turn affect their performance monitoring and is further explored in Study 1 of my thesis.

1.3 Study 1 Aims and Hypotheses

Previous research has confirmed a deficit in performance monitoring in children with ADHD. One explanation for atypical performance monitoring in children with ADHD is that
they have a diminished ability to detect errors in their performance, suggesting that the provision of knowledge of results would facilitate performance monitoring. This hypothesis is supported by a body of research documenting that children with ADHD often overestimate their skills, suggesting that they do not recognize errors in their performance. One goal of this study is to empirically test this hypothesis as this knowledge is critically important to the development of cognitive and behavioural interventions aimed at improving performance monitoring in children with ADHD.

In addition, it is not clear whether ADHD is characterized by a generalized deficit in performance monitoring (in which case children with ADHD show deficient performance monitoring after errors and correct responses), or a specific deficit in error processing (in which case children with ADHD have difficulty adjusting behaviour following errors, but not following correct performance). This distinction can help us understand how children with ADHD learn from both success and errors, and may lead to a clinical and educational understanding of potential interventions. In addition to its relevance to further conceptualizing ADHD, a better grasp of how performance monitoring functions in typically developing children is critical to the advancement of educational theory.

In Study 1 I aim to expand on our knowledge of performance monitoring of typically developing children and children with ADHD (the term “children” will be used to reflect individuals between the ages of 6 and 16 in this study) in two ways: (1) First, by determining whether ADHD is characterized by a generalized deficit in performance monitoring, or by a specific deficit in error processing, and (2) by examining if deficient performance monitoring in children with ADHD can be improved by providing accurate performance feedback (i.e., knowledge of results).
To address the above aims, participants were asked to perform a speeded choice reaction time task designed to generate both correct responses and errors. Participants were presented with two conditions of a modified Eriksen flanker task (Eriksen & Eriksen, 1974) in a counterbalanced order: A “Feedback” condition that provided knowledge of results and a “No Feedback” condition that did not. This manipulation aimed to facilitate performance monitoring by providing knowledge of results on every trial, thereby driving performance monitoring processes and reducing participants’ reliance on accurate self-detection of performance. This manipulation is a novel approach to research on children with ADHD. The flanker task was chosen as it has been widely used in the investigation of performance monitoring, elicits both correct responses and errors in the same task, evokes adjustment in reaction time, is amenable to performance feedback manipulation, and has task accuracy benefits when adjustment is employed (Dikman & Allen, 2000; Falkenstein et al., 1991).

If children with ADHD exhibit a generalized performance monitoring deficit, then they should adjust their reaction time less than controls following both correct and incorrect responses. If ADHD is associated with an error processing deficit only, which I predict based on the consistent findings of previous studies, then children with ADHD should adjust their reaction time less than controls after errors only, and not following correct responses.

If, as assumed by the premise of the bi-phasic model of performance monitoring, detection drives adjustment which results in greater task accuracy, then explicit feedback of correct and incorrect responses should facilitate detection and enhance subsequent adjustment and accuracy. Therefore, I hypothesize that feedback will enhance adjustment and accuracy in the control group. In fact, in the real world, performance feedback is provided to children from parents and teachers alike to do exactly that: facilitate and enhance a child’s subsequent
performance. Furthermore, children with ADHD are often provided with much more feedback from parents and educators than typically developing children are ((Rucklidge & Kaplan, 2000; Schatz et al., 2014), suggesting that children with ADHD are viewed as needing greater feedback to facilitate their behaviour and performance. If accurate performance knowledge is a challenge for children with ADHD, as is suggested by the research reviewed above, then the behavioural manipulation of providing explicit feedback on correct or incorrect responses should result in accurate performance knowledge for children with ADHD. However, in the current study I question the assumption that greater feedback (in the form of pointing out errors and correct responses only, and without any subsequent provision of knowledge, instructions, or strategy use) actually leads to enhanced performance in children with ADHD. Is it simply that those children with ADHD do not know that they are making mistakes, and that is why they do not adjust their behaviour appropriately? Or alternatively, is it that children with ADHD know that they are making errors, but struggle to use appropriate strategies and knowledge to adjust their behaviour accordingly? The present study attempts to answer to these questions as this knowledge is of importance to the development of interventions aimed at ameliorating the performance monitoring deficit in children with ADHD.

If children with ADHD display an error processing deficit relative to controls because they are unable to detect the accuracy of their performance, then the provision of knowledge of results in the Feedback condition should substantially reduce or eliminate any difference from controls in adjustment. If a difference in adjustment remains despite accurate knowledge of results, then the deficit found in ADHD cannot be mitigated by providing external performance feedback. I hypothesize that providing knowledge of results will not enhance adjustment or accuracy in the ADHD group because of the assumption that any error processing deficit in
ADHD is the result of an atypical dopaminergic system in ADHD, and not the result of inaccurate error detection.

In terms of secondary research questions, because performance monitoring is hypothesized to play a significant role in learning (Tam et al., 2013; Ullsperger, 2010), I aim to examine potential relationships between the two using measures of academic achievement. I predict that adjustment and scholastic achievement will not be significantly related in the present study because achievement measures are considered to be proxies of learning and not true learning tasks. In addition, previous research has shown that children with learning disabilities (both reading disability alone, and math and reading disabilities together) have atypical error processing independent of ADHD (Burgio-Murphy et al., 2007; Shafrir, Siegel, & Chee, 1990). I aim to determine if children with comorbid learning disability are driving any observed deficit in ADHD. I hypothesize that the possible contribution of weak error processing from children with comorbid learning disabilities will not account for any observed group differences because prior research has shown a deficit in children with ADHD alone.

Cognitive accounts of error processing posit that its processes are underpinned by working memory (Holroyd & Coles, 2002; Shiels & Hawk, 2010). Furthermore, research has indicated that children with ADHD possess deficits in their working memory (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005). Therefore, I aim to examine the potential relationship between working memory and adjustment. I predict that a significant relationship will be found between these two processes because theories suggest that updating of working memory is required in order to use errors to adjust one’s behaviour.

Task reaction times, and therefore adjustment, can be influenced by several factors. Therefore, to determine that any observed group differences in adjustment are not simply the
result of group differences in response speed, age, IQ, or gender, these variables will be assessed between groups and controlled for in analyses if they are significantly related to adjustment. I hypothesize that these sample characteristics will not account for group differences in adjustment because previous research has indicated a deficit in performance monitoring in children with ADHD independent of these variables (Schachar et al., 2004).

The relationship between performance monitoring and other sample characteristics of subtype, impairment, and severity in the ADHD group will also be investigated to assess any potential unique relationships between adjustment and ADHD. I posit that no significant relationships will be found because only two previous studies have found any such associations, and their findings are inconsistent. One of these studies found an association between a deficit in performance monitoring and the inattentive ADHD subtype (Shiels et al., 2012), and the other an association between the deficit and increased symptom severity (Schachar et al., 2004).

Lastly, the relationship between adjustment and accuracy will be examined to determine if greater adjustment is related to greater accuracy. I hypothesize that increased accuracy will be significantly related to increased adjustment because it is adaptive to adjust one’s behaviour as it leads to enhanced performance.
2. Chapter 2 - Study 1 Method

2.1 Participants

Children with ADHD were drawn from referrals to a clinic specializing in children with attention, learning and behaviour problems in a large urban pediatric hospital. Controls (also referred to as typically developing children) were recruited through advertisement within the hospital. Participants ranged in age from 6 to 16 years old and were attending a primary or secondary school, ensuring that both a parent and a teacher could serve as informants. The sample was drawn from communities surrounding the hospital, yielding a pool of participants who were likely representative of the ethnicity and socioeconomic status of the communities from which they were drawn. All participants were required to be free of psychotropic medication for at least 24 hours prior to testing because of the potential impact of medications on adjustment or task accuracy (Barnes et al., 2014; Groom et al., 2013).

The Parent Interview for Child Symptoms (PICS-IV; Ickowicz et al., 2006) was used in the parent interview portion of the ADHD assessment. The PICS-IV covers DSM-IV-TR (American Psychiatric Association, 2000) criteria for ADHD and other Axis I diagnoses, and covers developmental, medical, and social histories. The reliability of this interview is high (e.g., \( \kappa = 80\% \) for ADHD; intraclass correlation \( \gamma > .90 \)). The Teacher Telephone Interview (TTI-IV; Tannock, Hum, Masellis, Humphries, & Schachar, 2002) is a 30 minute interview that was administered to teachers over the telephone by a trained interviewer. The TTI-IV covers symptoms of ADHD and screens for other disorders. For both of these instruments, symptom presence was rated using specific criteria in an extensive manual. All interviewers were also trained to a criterion of 90% symptom agreement before interviewing parents or teachers. A social worker or nurse with extensive experience conducted the parent interview and a research
coordinator with a Master’s degree in psychology conducted the teacher interview. Children’s
parents and teachers were given several diagnostic and behavioural questionnaires prior to clinic
admission. These were the Conners’ Parent Rating Scales Revised Long Version, (CPRS-R:L;
Conners, 1997), Conners’ Teacher Rating Scales Revised Long Version (CTRS-R:L; Conners,
1997), and the Ontario Child Health Study Scales (OCHS; Boyle, Offord, Racine, & Fleming,
1993). When the child’s teacher had not observed the child without medication within the
preceding 6 months, a drug free trial of at least 3 days was arranged prior to teacher ratings and
interviews. As typically developing children were not assessed with parent and teacher
interviews (PICS-IV and TTI-IV) due to time constraints, the parent and teacher Conners’ Rating
Scales (Conners, 1997) and OCHS scales (Boyle et al., 1993) of potential controls were screened
prior to research testing in order to ensure that these children met criteria for the control group.

All children being assessed for ADHD received an assessment of cognitive,
psychoeducational, language, and social-emotional functioning. Typically developing children
received an abbreviated assessment of cognitive, psychoeducational, and social-emotional
functioning. A psychological associate, supervised by a registered clinical psychologist,
assessed intellectual ability using the Wechsler Intelligence Scale for Children 4th ed. (WISC-
IV; Wechsler, 2003) for the ADHD group, and the Wechsler Abbreviated Scale of Intelligence
(WASI) for the controls. Other measures, such as the Digit Span Forwards and Backwards
Subtests of the WISC-IV were administered as part of a larger research battery. Academic
achievement was assessed in reading and arithmetic through a comprehensive battery of
achievement tests (Woodcock Reading Mastery Test Revised, WRMT-R; Woodcock, 1987;
Wide Range Achievement Test 3rd ed., WRAT-III; Wilkinson, 1993). All academic measures
used were normed using age. Children also completed self-report measures of anxiety symptoms
(Multidimensional Anxiety Scale for Children, MASC; March, Parker, Sullivan, Stallings, & Connors, 1997), and depression (Children’s Depression Inventory, CDI; Kovacs, 1985). A global measure of impairment was obtained by having parents and teachers rate each participant on the Ontario Child Health Survey Scales (OCHS; Boyle et al., 1993). Impairment scores were standardized by age and gender using general population norms. Children being assessed for ADHD received a hearing (pure tone audiometric screening), vision (screening of visual acuity), and language assessment by a registered speech pathologist using the Clinical Evaluation of Language Fundamentals 3rd. ed. (CELF-III; Semel, Wiig, & Secord, 1995).

For clinic-referred children, all of the measures and information gathered as outlined above were used by a clinical team composed of a psychiatrist, psychologist, social worker/nurse, and speech language pathologist to determine any clinical diagnoses including ADHD, oppositional defiant disorder, conduct disorder, depression, separation anxiety, generalized anxiety, and learning disability.

2.1.1 Inclusion criteria

To be classified as ADHD for research purposes, children had to meet DSM-IV-TR criteria for ADHD (American Psychiatric Association, 2000) defined as at least 6 of 9 inattentive, 6 of 9 hyperactive/impulsive symptoms, or both. To ensure that children were at least moderately impaired in two settings as per the DSM-IV-TR, it was required that they met criteria for ADHD from the parent or the teacher interview and questionnaires, and a minimum of 4 ADHD symptoms were reported according to the second informant, with a “moderately impaired” rating on both the parent and teacher impairment scales. Participants were categorized into ADHD subtypes (Inattentive, Hyperactive/Impulsive, or Combined) based on all
information and using DSM-IV-TR criteria (see Appendix A for DSM-IV-TR criteria for ADHD and ADHD subtypes).

Control participants were included in this study if they did not meet DSM-IV-TR criteria for ADHD on the parent or teacher Conners’ Rating Scales (Conners, 1997) defined as obtaining T-Scores less than 60 on the DSM-IV Inattentive, DSM-IV Hyperactive-Impulsive, and DSM-IV Total subscales. Typically developing children were also included if no other behavioural, psychiatric, hearing, language, or learning problems were endorsed on the OCHS scales (Boyle et al., 1993), or on the self-report measures of the MASC (March et al., 1997) and CDI (Kovacs, 1985).

2.1.2 Exclusion criteria

Participants were excluded if they fulfilled any of the following criteria: (a) Full Scale IQ below 80 on the WISC-IV, (b) presence of a serious medical condition, substance abuse, a history of traumatic brain injury from parent-reported history, (c) concurrent treatment with medication other than a stimulant, (d) specific language impairment (as defined by a CELF total language score below 85) as this may interfere with assessment and cognitive testing, or (e) hearing or visual impairment. Fourteen ADHD participants were excluded due to language impairment and 4 due to low IQ from the 76 cases assessed.

Control participants were excluded from this study if they obtained T-Scores greater than or equal to 60 on the DSM-IV Inattentive, DSM-IV Hyperactive-Impulsive, or DSM-IV Total subscales of the parent or teacher Conners’ Rating Scales (Conners, 1997) thereby meeting criteria for ADHD. Typically developing children were also excluded if any other behavioural, psychiatric, hearing, language or learning problems were endorsed on the OCHS scales (Boyle et
al., 1993), or on the self-report measures of the MASC (March et al., 1997) and CDI (Kovacs, 1985). Using these criteria no control participants were excluded in the present study from the 33 assessed.

Outliers, defined as scores + or – 3 standard deviations from the mean of the dependent measures of post-correct and post-error adjustment in either condition, were excluded from all analyses. This excluded one control and one ADHD participant.

After applying all inclusion and exclusion criteria, there were a total of 32 typically developing children (controls) and 57 children with ADHD who participated in this study.

2.2 Measures

Two conditions of a modified Eriksen flanker task (Eriksen & Eriksen, 1974) were presented using identical stimuli and instruction sets (see Figure 1). Both versions of the task were administered on a computer using Presentation software (Neurobehavioural Systems Inc.) to control the presentation and timing of all stimuli. Each version of the task consisted had 25 trials presented in 5 blocks for a total of 125 trials. Within each task, a practice block was run prior to the test block being administered. A fixation symbol, “*”, was displayed at the beginning of each trial for 500 ms. Participants were instructed to respond with a left or right hand response using a hand-held response box/game controller. Following the presentation of the fixate, a stimulus array was presented on screen for 150 ms, during which time a participant could respond and move onto the next trial. If the participant did not respond within the 150 ms stimulus display time, a visual mask consisting of a grey bar covering the same dimensions of the array was presented for 350 ms to prevent any visual after effects of the stimulus array. Participants were also able to respond during the visual mask. If a response was still not made,
the visual mask was followed by a blank screen which allotted an additional 1500 ms for the participant to respond. Once a response was made, participants moved onto the next trial.

Stimuli consisted of an array of five white letters presented on a black background in the centre of the computer screen, where the middle letter was always the target. To increase task difficulty (thereby increasing error rates), four different letters were used as targets. Targets M and N were mapped to the left index finger, and targets S and H were mapped to the right index finger. There were eight sequences of stimuli that were presented randomly within each block (see Figure 1). On every trial each target was flanked by distracter stimuli that were associated with the opposite or conflicting response as the target. In other words, all trials had distracters that were incongruent with the target (e.g., HHMH, SSNS, NNHN, HHHH). The incongruent condition generates longer reaction times and greater error rates than the congruent condition as a result of cognitive and motor conflict between the target and the distracters during response selection (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). There were 63 trials with S or H as a target, and 62 trials with M or N as a target.

The two conditions that were employed were a “no feedback” condition, where participants were not provided with any indication of how they were performing, and a “feedback” condition, where participants were provided with knowledge of their performance on each trial throughout the entire task. Participants in both groups received identical instructions for each version of the task and were instructed to be as accurate as possible while performing the task as fast as possible. Possible practice effects were eliminated by counterbalancing the order in which participants completed the conditions. A detailed description of each condition follows.
2.2.1 No Feedback Condition

In the no feedback condition, participants were presented with a neutral auditory tone immediately following each response. The tone did not vary and was identical regardless of task accuracy. Participants were told that the tones were the computer acknowledging that they had provided a response and that the tones did not represent any information regarding performance. Debriefing and observation of participants during the practice block before beginning this condition indicated that they understood task instructions.

2.2.2 Feedback Condition

In the feedback condition, participants received valid auditory feedback immediately following a response. A high pitched tone emitted from the computer speakers indicated a correct response, and low pitched tone indicated an incorrect response (or no response, which is still incorrect). These tones provided participants with explicit knowledge of their performance and the meaning of the feedback tones was explained to participants. Debriefing and observation of participants during the practice block before beginning this condition indicated that they understood task instructions and could discriminate between the feedback tones and their meaning.
Figure 1. Representation of a trial from the modified flanker task

Stimuli:
NNSNN
MMSMM
NNHNN
MMHMM
HHMHH
SSMSS
SSNSS
HHNHH

Middle letter is target stimulus

Tone emitted immediately after response or at 2500 ms

No Feedback Condition

Feedback Condition
2.3 Procedure

All procedures were explicitly outlined in our information and consent forms and were approved by the research ethics board at The Hospital for Sick Children. Informed consent and assent was obtained prior to participation in research testing. The parent, teacher, and child assessments were conducted without knowledge of the screening diagnosis or the results of other portions of research testing, including the results of the modified flanker tasks. All children were free of medication for at least 24 hours on the day of research testing.

The same research assistants administered tasks to both groups and the physical testing set up was also the same across groups. Research assistants ensured task understanding and valid performance of the practice block before testing. During testing, task validity was also evaluated by monitoring participants’ responses. Within the larger research battery, the type of task (e.g. pencil and paper, computerized, working memory, or inhibitory control task) that was administered before, after, or between the modified flanker tasks was randomized.

2.4 Analyses

2.4.1. Dependent Variables

Three dependent variables were obtained for analyses in each condition of the flanker task. All dependent variables are listed in Table 1. The calculated measures of post-correct and post-error adjustment are considered to be behavioural indices of performance monitoring in the tasks used. Participants’ task accuracy (i.e., percent correct) was directly measured by observing the number of target stimuli correctly identified in each condition. Given that the present study is based on the premise that it is adaptive to adjust one’s performance during a task, accuracy
was measured in order to examine any relationship to adjustment, and any possible group differences.

Table 1

List of Dependent Variables

<table>
<thead>
<tr>
<th>Name of Variable</th>
<th>What Variable Represents</th>
<th>How is Variable Measured or Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-Correct Adjustment (ms)</td>
<td>Amount of adjustment after correct trials, relative to mean reaction time on correct trials</td>
<td>Calculated as: mean post-correct reaction time minus mean correct reaction time</td>
</tr>
<tr>
<td>Post-Error Adjustment (ms)</td>
<td>Amount of adjustment after errors, relative to mean reaction time on correct trials</td>
<td>Calculated as: mean post-error reaction time minus mean correct reaction time</td>
</tr>
<tr>
<td>Accuracy (percent correct)</td>
<td>Percentage of total correct trials in a task</td>
<td>Directly measured from task</td>
</tr>
</tbody>
</table>

2.4.2. Statistics

In order to evaluate the effects of group membership and feedback on adjustment after errors and correct responses and on task accuracy, a mixed design Multivariate Analysis of Variance (MANOVA) was conducted with the between-subjects factor being group membership (i.e., ADHD vs. Control), and the within-subjects factor being condition (i.e., No Feedback vs. Feedback). In order to protect against inflated Type 1 error rates, if the MANOVA was non-significant (i.e., the null hypothesis was true), then no further tests were performed. A significant MANOVA was followed up by a post-hoc mixed design Univariate Analyses of Variance (ANOVA) on each dependent variable. Adjustment was correlated with age, gender, task accuracy, symptom severity, impairment, academic and working memory measures. In order to address secondary research questions or particular results, follow-up and covariate analyses were conducted where appropriate.
3. Chapter 3 - Study 1 Results

Assumptions of normality and homogeneity of variance were not violated in the following analyses. No participant had 100% accuracy which would have precluded analysis of post-error adjustment and no participant had accuracy of less than 40% which would have suggested near random responding.

3.1 Sample Characteristics

Sample characteristics can be found in Table 2 below. Groups did not significantly differ on age ($t(87)=1.29, \text{n.s.}$), but were significantly different on IQ ($t(87)=6.07, p < .000$) and on their gender proportions ($\chi^2 (1) = 15.92, p < .000$). Children with ADHD and typically developing children significantly differed on the Conners’ Parent Rating Scale DSM-IV: Total Subscale T-Score ($t(87)=11.95, p < .000$) and Conners’ Teacher Rating Scale DSM-IV: Total Subscale T-Score ($t(87)=10.91, p < .000$). The groups also significantly differed on achievement scores: Single Word Reading Standard Scores (WRMT-R) - $t(87)=4.20, p < .000$; Reading Comprehension Standard Score (WRAT-III) - $t(87)=4.01, p < .000$; Spelling Standard Score (WRAT-III) - $t(87)=5.61, p < .000$; Arithmetic Standard Score (WRAT-III) - $t(87)=4.75, p < .000$. 
Table 2

Summary of Sample Characteristics for Study 1

<table>
<thead>
<tr>
<th>Demographics</th>
<th>Control (N = 32)</th>
<th>ADHD (N = 57)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Male: 34% Female: 66%</td>
<td>Male: 77% Female: 23%</td>
</tr>
<tr>
<td>Age (years)</td>
<td>Mean: 10.4 SD: 3.3</td>
<td>Mean: 9.7 SD: 2.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Academic / Psychoeducational Measures</th>
<th>Control (N = 32)</th>
<th>ADHD (N = 57)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IQ</td>
<td>Mean: 116.4 SD: 11.5</td>
<td>Mean: 101.1 SD: 11.4</td>
</tr>
<tr>
<td>Single Word Reading Standard Score (WRMT-R)</td>
<td>111.9 SD: 12.2</td>
<td>98.4 SD: 15.4</td>
</tr>
<tr>
<td>Reading Comprehension Standard Score (WRAT-III)</td>
<td>113.2 SD: 9.8</td>
<td>99.9 SD: 13.2</td>
</tr>
<tr>
<td>Spelling Standard Score (WRAT-III)</td>
<td>111.8 SD: 12.2</td>
<td>93.0 SD: 13.9</td>
</tr>
<tr>
<td>Arithmetic Standard Score (WRAT-III)</td>
<td>106.8 SD: 15.0</td>
<td>92.8 SD: 12.1</td>
</tr>
<tr>
<td>Digit Span Forwards Scaled Score (WISC-IV)</td>
<td>12.2 SD: 3.2</td>
<td>9.1 SD: 2.8</td>
</tr>
<tr>
<td>Digit Span Backwards Scaled Score (WISC-IV)</td>
<td>11.4 SD: 3.1</td>
<td>10.3 SD: 3.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Clinical Measures</th>
<th>Control (N = 32)</th>
<th>ADHD (N = 57)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conners’ Parent Rating Scale DSM-IV: Total Subscale (T-Score)</td>
<td>46.8 SD: 5.4</td>
<td>72.2 SD: 11.2</td>
</tr>
<tr>
<td>Conners’ Teacher Rating Scale DSM-IV: Total Subscale (T-Score)</td>
<td>46.4 SD: 5.3</td>
<td>69.0 SD: 9.4</td>
</tr>
<tr>
<td>Parent and Teacher Rated Symptom Severity Summary Score (PICS-IV and TTI-IV)</td>
<td>- -</td>
<td>20.3 SD: 5.2</td>
</tr>
<tr>
<td>Parent and Teacher Rated Impairment Scaled Score (OCHS)</td>
<td>- -</td>
<td>10.0 SD: 5.4</td>
</tr>
<tr>
<td>Clinician Rated Impairment Score (CGAS)</td>
<td>- -</td>
<td>53.9 SD: 6.8</td>
</tr>
</tbody>
</table>
The sample of children with ADHD was composed of a heterogeneous group with associated or comorbid diagnoses typical of clinic samples (please see Table 3).

Table 3

Diagnoses in ADHD Sample for Study 1

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of Participants (N)</th>
<th>Percentage of Participants (%)</th>
<th>Diagnoses</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADHD</td>
<td>25</td>
<td>44%</td>
<td>ADHD – Combined Type</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>39%</td>
<td>ADHD – Inattentive Type</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>17%</td>
<td>ADHD – Hyperactive/Impulsive Type</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2%</td>
<td>Conduct Disorder</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2%</td>
<td>Depression</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5%</td>
<td>Separation Anxiety</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>14%</td>
<td>Generalized Anxiety (GAD)</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>19%</td>
<td>Learning Disability (LD)</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>32%</td>
<td>Oppositional Defiant Disorder (ODD)</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>26%</td>
<td>None</td>
</tr>
</tbody>
</table>

3.2 Main and Interaction Effects

Means and standard deviations for all dependent variables are listed in Table 4. Results of a mixed design MANOVA indicated that there was a significant multivariate interaction of group and condition across all dependent variables \( F(3,85) = 3.40, p < .025 \). Follow-up post-hoc univariate ANOVA analyses were conducted on each dependent variable and are listed in Table 5.
No significant interaction or main effect of group or condition was found on post-correct adjustment (see Figure 2). A significant interaction between group and condition on post-error adjustment was found \((F(1, 87) = 5.84, p < .02;\) see Figure 3). A significant interaction between group and condition on task accuracy was also found \((F(1, 87) = 4.31, p < .05;\) see Figure 4). These results indicate that the Feedback condition differentially affected post-error adjustment and accuracy in controls and children with ADHD. To determine how each group was differentially affected, t-tests were conducted to examine these significant interactions more closely. Only controls showed a significant increase in post-error adjustment (Controls: \(t(31) = 2.85, p = .008;\) ADHD: \(t(56) = .61, n.s.\)) and task accuracy (Controls: \(t(31) = 2.89, p < .01;\) ADHD: \(t(56) = 0.92, n.s.\)) in the Feedback condition compared to the No Feedback condition. Cohen’s effect size value also suggested a moderate effect of condition on post-error adjustment (Controls: \(d = .55;\) ADHD: \(d = .09\)) and on task accuracy (Controls: \(d = .62;\) ADHD: \(d = .09\)) for typically developing children only. Additionally, only in the Feedback condition did controls show greater post-error adjustment (No Feedback: \(t(87) = 0.51, n.s.\); Feedback: \(t(87) = 2.94, p = .004\)) and task accuracy (No Feedback: \(t(87) = 1.19, n.s.\); Feedback: \(t(87) = 3.10, p < .005\)) than children with ADHD. Cohen’s effect size value also suggested a moderate to large effect of group on post-error adjustment (No Feedback: \(d = .11;\) Feedback: \(d = .62\)) and on task accuracy (No Feedback: \(d = .27;\) Feedback: \(d = .74\)) in the Feedback condition.

Overall, these results indicate a significant effect of performance feedback on adjustment following an error and on task accuracy in the control group. When provided with knowledge of results, controls adjusted their behaviour by significantly slowing their reaction time after making errors and increased accuracy, whereas children with a diagnosis of ADHD did not.
Table 4

Means and Standard Deviations of Dependent Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Controls</th>
<th></th>
<th>ADHD</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>No Feedback Condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Correct Adjustment (ms)</td>
<td>-1.6</td>
<td>31.2</td>
<td>5.3</td>
<td>40.7</td>
</tr>
<tr>
<td>Post-Error Adjustment (ms)</td>
<td>25.3</td>
<td>142.8</td>
<td>11.4</td>
<td>109.7</td>
</tr>
<tr>
<td>Accuracy (percent correct)</td>
<td>79.5</td>
<td>12.4</td>
<td>75.8</td>
<td>14.9</td>
</tr>
<tr>
<td>Feedback Condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Correct Adjustment (ms)</td>
<td>-11.0</td>
<td>27.3</td>
<td>0.04</td>
<td>45.0</td>
</tr>
<tr>
<td>Post-Error Adjustment (ms)</td>
<td>111.8</td>
<td>167.9</td>
<td>21.5</td>
<td>120.1</td>
</tr>
<tr>
<td>Accuracy (percent correct)</td>
<td>86.0</td>
<td>8.2</td>
<td>77.1</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Table 5

Univariate ANOVA Post-Hoc Results

<table>
<thead>
<tr>
<th>Variable</th>
<th>Main Effect of Group</th>
<th>Main Effect of Condition</th>
<th>Interaction of Group and Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>p-value</td>
<td>Effect Size (ƞ^2)</td>
</tr>
<tr>
<td>Post-Correct Adjustment (ms)</td>
<td>1.63</td>
<td>.205</td>
<td>.018</td>
</tr>
<tr>
<td>Post-Error Adjustment (ms)</td>
<td>4.62</td>
<td>.034*</td>
<td>.050</td>
</tr>
<tr>
<td>Accuracy (percent correct)</td>
<td>5.35</td>
<td>.023*</td>
<td>.058</td>
</tr>
</tbody>
</table>

Note. *indicates significance at the 0.05 level, **indicates significance at the 0.005 level.
There was no significant main effect or interaction of condition or group on post-correct adjustment indicating no significant differences between children with ADHD and controls across conditions on post-correct adjustment.

This significant interaction of group and condition on post-error adjustment reveals that the Feedback condition caused a significant post-error adjustment of slowing in the control group, but not in the ADHD group. T-tests revealed that controls, but not ADHD, showed significantly different post-error adjustment across conditions (Controls: t(31)=2.85, p = 0.008; ADHD: t(56)=0.61, n.s.). There were significant group differences in the Feedback condition, but not in the No Feedback condition (No Feedback t(87)=0.51, n.s., Feedback t(87)=2.94, p = 0.004).
This significant interaction of group and condition on accuracy suggests reveals that the Feedback condition was associated with a significant increase in accuracy for the control group, but not for the ADHD group. T-tests revealed that controls showed significantly greater accuracy across conditions (Controls: $t(31)=2.89$, $p < 0.01$; ADHD: $t(56)=0.92$, n.s.). There were significant group differences in the Feedback condition, but not the No Feedback condition (No Feedback $t(87)=1.19$, n.s., Feedback $t(87)=3.10$, $p < 0.005$).

### 3.3 Correlates of Adjustment

There was no significant relationship between full scale IQ and post-correct or post-error adjustment across groups and conditions (see Table 4). Analyses revealed that age was related to post-correct adjustment across groups and conditions ($r(89) = -0.24$, $p = 0.025$). Older children, regardless of ADHD status, displayed less post-correct adjustment compared to younger children across conditions. Within the ADHD group, ADHD symptom severity (i.e., the total number of ADHD symptoms reported by parents and teachers combined), and impairment (both parent and teacher reported measures of impairment obtained from the OCHS Scales (Boyle et al., 1993),
and clinician rated measures of impairment on the Children’s Global Assessment Scale (CGAS; Shaffer, Gould, Bird, et al., 2000), did not correlate with adjustment across conditions.

For both conditions, a highly significant relationship was found between accuracy and adjustment across groups. Increased accuracy was related to less post-correct adjustment (No Feedback: $r(89) = -.24, p < .005$; Feedback: $r(89)= -.10, p < .0005$), and related to greater post-error adjustment (No Feedback: $r(89) = .39, p < .0005$; Feedback: $r(89)= .40, p < .0005$) across groups. Further analyses were conducted to determine if adjustment was related to accuracy in other measures (for correlations see Table 4). In the control group, adjustment was not correlated with any academic or working memory measures. In the ADHD group, results revealed a significant positive correlation between post-correct adjustment (not post-error adjustment) across conditions and performance on word reading (WRMT-R Word Identification and Work Attack Subtests; Woodcock, 1987), spelling (WRAT-III Spelling Subtest; Wilkinson, 1993), and math achievement scores (WRAT-III Arithmetic Subtest; Wilkinson, 1993). However, measures of reading comprehension (WRAT-III Global Reading Score; Wilkinson, 1993) and working memory (i.e., digit span forwards and backwards standard scores on the WISC-IV; Wechsler, 2003) were not significantly related to adjustment in the ADHD group across conditions.
Table 6
Correlates of Adjustment in Study 1

<table>
<thead>
<tr>
<th>Across Groups</th>
<th>Post-Correct Adjustment</th>
<th>Post-Error Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r(89)$</td>
<td>$p$-value</td>
</tr>
<tr>
<td>Demographics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>-.24</td>
<td>.025*</td>
</tr>
<tr>
<td>Accuracy</td>
<td>No Feedback: -.29</td>
<td>.005**</td>
</tr>
<tr>
<td></td>
<td>Feedback: -.38</td>
<td>&lt;.0005***</td>
</tr>
<tr>
<td>Controls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Academic/Psychoeducational Measures</td>
<td>$r(32)$</td>
<td>$p$-value</td>
</tr>
<tr>
<td>Full Scale IQ (WASI)</td>
<td>.12</td>
<td>.517</td>
</tr>
<tr>
<td>Single Word Reading (WRMT-R)</td>
<td>.05</td>
<td>.783</td>
</tr>
<tr>
<td>Reading Comprehension (WRAT-III)</td>
<td>.04</td>
<td>.856</td>
</tr>
<tr>
<td>Spelling (WRAT-III)</td>
<td>.02</td>
<td>.915</td>
</tr>
<tr>
<td>Arithmetic (WRAT-III)</td>
<td>-.16</td>
<td>.384</td>
</tr>
<tr>
<td>Digit Span Forwards (WISC-IV)</td>
<td>-.39</td>
<td>.066</td>
</tr>
<tr>
<td>Digit Span Backwards (WISC-IV)</td>
<td>-.25</td>
<td>.254</td>
</tr>
<tr>
<td>ADHD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Academic/Psychoeducational Measures</td>
<td>$r(57)$</td>
<td>$p$-value</td>
</tr>
<tr>
<td>Full Scale IQ (WISC-IV)</td>
<td>.19</td>
<td>.153</td>
</tr>
<tr>
<td>Single Word Reading (WRMT-R)</td>
<td>.44</td>
<td>.001**</td>
</tr>
<tr>
<td>Reading Comprehension (WRAT-III)</td>
<td>.21</td>
<td>.210</td>
</tr>
<tr>
<td>Spelling (WRAT-III)</td>
<td>.41</td>
<td>.024*</td>
</tr>
<tr>
<td>Arithmetic (WRAT-III)</td>
<td>.47</td>
<td>&lt;.0005***</td>
</tr>
<tr>
<td>Digit Span Forwards (WISC-IV)</td>
<td>-.02</td>
<td>.872</td>
</tr>
<tr>
<td>Digit Span Backwards (WISC-IV)</td>
<td>.06</td>
<td>.656</td>
</tr>
</tbody>
</table>
### Clinical Measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean 1</th>
<th>Mean 2</th>
<th>Mean 3</th>
<th>Mean 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent and Teacher Rated Symptom Severity</td>
<td>.25</td>
<td>.058</td>
<td>-.08</td>
<td>.537</td>
</tr>
<tr>
<td>(PICS-IV and TTI-IV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parent and Teacher Rated Impairment (OCHS)</td>
<td>-.11</td>
<td>.409</td>
<td>.12</td>
<td>.402</td>
</tr>
<tr>
<td>Clinician Rated Impairment (CGAS)</td>
<td>-.03</td>
<td>.844</td>
<td>.13</td>
<td>.388</td>
</tr>
</tbody>
</table>

*Note.* *indicates significance at the 0.05 level, **indicates significance at the 0.005 level, and ***indicates significance at the 0.0005 level.

#### 3.4 Secondary Analyses

In order to determine that the differences found in adjustment were not a function of differences in overall reaction times or reaction time variability, a follow-up univariate analysis was conducted comparing the reaction times of the ADHD and control group. Results revealed that the mean reaction time on correct \(F(1,87) = 0.42, \text{n.s.}\) and incorrect trials \(F(1,87) = 2.79, \text{n.s.}\), and their variability (Correct Response Time Variability: \(F(1,87) = 1.13, \text{n.s.}\); Incorrect Response Time Variability: \(F(1,87) = 3.21, \text{n.s.}\) was not significantly different between groups.

To examine any potential differences between the three ADHD subtypes (as defined in the DSM-IV), a follow-up univariate analysis comparing subtype groups on dependent variables was conducted. Results revealed that post-correct adjustment \(F(2,54) = 2.10, \text{n.s.}\), post-error adjustment \(F(2,54) = 2.46, \text{n.s.}\), and task accuracy \(F(2,54) = 1.63, \text{n.s.}\) were not significantly different between ADHD subtypes.

To examine any potential differences between genders on adjustment, follow-up t-tests comparing males to females across groups on post-correct and post-error adjustment across conditions was conducted. Results revealed that post-correct adjustment \(t(87) = 0.89, \text{n.s.}\) and post-error adjustment \(t(87) = 1.76, \text{n.s.}\) were not significantly different between genders.
Age was correlated with post-correct adjustment ($r(89) = -.24$, $p = .025$) across groups and conditions with older children, regardless of ADHD status, displaying less post-correct adjustment compared to younger children. A mixed design MANCOVA indicated that once age was controlled for the previous results of the study remained significant. There remained a significant multivariate interaction of group and condition across all dependent variables ($F(3,84) = 3.45$, $p = .02$). Post-hoc univariate ANCOVA analyses also found the same results even when age was controlled for. No significant interaction or main effect of group or condition was found on post-correct adjustment. A significant interaction between group and condition on post-error adjustment ($F(1, 86) = 6.22$, $p = .015$), and on task accuracy was found ($F(1, 86) = 4.04$, $p < .05$).

There were 11 children with ADHD and comorbid learning disability (LD; 3 children with comorbid ADHD and math disability, 6 children with comorbid ADHD and reading disability, and 2 children with comorbid ADHD and both a math and reading disability). This subgroup of children with ADHD and comorbid learning disability (LD) was removed from the ADHD group. The remaining ADHD participants without any comorbid LD were compared to controls on dependent variables using a mixed design MANOVA. There remained a significant multivariate interaction of group and condition across all dependent variables ($F(3,74) = 2.77$, $p < .05$). Post-hoc univariate ANOVA results revealed that post-correct adjustment ($F(1,76) = 3.24$, n.s.) remained similar across groups. Post-error adjustment ($F(1,76) = 5.68$, $p = .02$) and task accuracy ($F(1,76) = 3.99$, $p < .05$) remained significantly different between the ADHD and control groups across conditions. ADHD participants continued to show significantly less post-error adjustment ($t(76) = 3.09$, $p = .003$) and accuracy ($t(76) = 2.75$, $p = .008$) than controls within the Feedback condition.
4. Chapter 4 - Study 1 Discussion

The aims of the Study 1 were to determine whether ADHD is characterized by a generalized deficit in performance monitoring, or by a specific deficit in error processing, and to examine if any deficit in children with ADHD can be improved by providing accurate performance feedback (i.e., knowledge of results).

Results indicated that children with ADHD made more errors and had less post-error adjustment across conditions compared to controls. These results confirm previous reports of a performance monitoring deficit in children with ADHD. When provided with performance feedback, typically developing children displayed significantly greater post-error adjustment and improved task accuracy. In contrast, children with ADHD did not show significantly improved post-error adjustment or task accuracy with accurate knowledge of results. Therefore, as was hypothesized, the deficit in children with ADHD was not attenuated by pointing out errors and correct responses. A detailed discussion of the possible effects of feedback follows in the subsequent section.

In contrast to the significant difference between groups on post-error adjustment, typically developing children and those with ADHD did not significantly differ on post-correct adjustment across conditions. As was hypothesized, this result suggests that the deficit found in children with ADHD is specific to error-processing, and is consistent with previous reports of such a deficit in children with ADHD (Spinelli et al., 2011; Jonkman et al., 2007; Wiersema, et al., 2005; Sergeant & van der Meere, 1988; Schachar et al., 2004; Krusch et al., 1996).

Although there was no significant difference in post-correct adjustment between groups, typically developing children appeared to modulate their adjustment (i.e., reaction times) following both errors and correct responses to a greater extent than children with ADHD did.
All participants were instructed to be as accurate and as fast as possible when performing the modified flanker tasks. Such a task has both speed and accuracy requirements, indicating the potential of a speed accuracy trade-off (SATO), meaning that speed may be traded-off for accuracy, and accuracy for speed (Brewer & Smith, 1984). SATO tasks must be completed as fast as possible without sacrificing accuracy, causing participants to attempt to find reaction time ranges (termed reaction time bands) that are just safely above those reaction times at which errors are likely to occur (i.e., fast-accurate reaction time bands; Brewer & Smith, 1984). Similarly, when participants commit errors, they learn those reaction time ranges that are associated with an increased likelihood of errors (i.e., fast-inaccurate reaction time bands) (Brewer & Smith, 1984). In the case of correct responses on such SATO tasks, participants are accurate at the speed they are responding, so it would be advantageous for them to speed up and find the optimal reaction time band, thereby being as fast and accurate as possible. In fact, pushing reaction time boundaries is adaptive given SATO task instructions. In the case of errors, participants are not accurate because they may be executing responses too quickly, so going slower may be advantageous and enhance accuracy, thereby being as accurate and fast as possible.

Indeed, in the present study controls displayed on average faster post-correct adjustment, meaning they sped up their reaction time on correct trials following correct trials. It is likely that when control participants’ knew that they were performing correctly, both when self-detecting their performance and when receiving feedback, they continued to use similar strategies/knowledge used on previous successful trials and responded faster. In contrast, after errors, controls slowed down in order to reassess and/or modify the strategies being used to perform the task and to achieve accurate performance. Therefore, typically developing children
performed as expected, they sped up after correctly responding and sought the limits of this speed while maintaining task accuracy, and they slowed after making errors in order to enhance accuracy. Looking across both post-correct and post-error adjustment, controls do not appear to be indiscriminately slowing or speeding up; rather they are strategically doing so as demonstrated by the strong correlations between accuracy and adjustment. Post-correct adjustment was negatively correlated with greater accuracy across groups. This further suggests that it is adaptive to speed up one’s reaction time following correct responses on the modified flanker tasks employed in this study. In contrast, the opposite relationship was found between post-error adjustment and accuracy across groups. This result suggest that it is adaptive to slow down following errors on the modified flanker tasks used. These findings support the validity of these tasks and their use as a paradigm to assess both post-correct and post-error adjustment.

This adaptive modulation displayed by typically developing children suggests that they are seeking out the limits of the fast-accurate reaction time band in the context of the modified flanker tasks used. In contrast, children with ADHD do not show the same pattern of adjustment modulation. Firstly, they did not (on average) speed up following correct responses as controls did across conditions. Secondly, the ADHD group showed similar post-correct ($M = 5.3$ ms) and post-error adjustment ($M = 11.4$ ms) in the No Feedback condition. These results suggests that children with ADHD are either satisfied with how well they are performing and see no reason to adjust their reaction time (i.e., respond faster or slower); or, they struggle with modulating their behaviour in order to respond faster or slower and maintain accuracy (i.e., find the optimal fast-accurate reaction time band). The latter explanation supports a deficit in ADHD with regards to modulating and making adjustments to future behaviour in response to previous performance.
In summary, the results of the present study indicate that children with ADHD have a deficit specific to error processing as measured by their post-error adjustment, and likely have difficulty with modulation of cognitive and behavioural processes involved in adjusting their performance. The error processing deficit in ADHD was most significantly observed in the Feedback condition when knowledge of results was provided. Therefore, being provided with explicit feedback about errors did not ameliorate the error processing deficit in the ADHD group. Rather, this result supports the notion that children with ADHD are atypical in using knowledge of errors to their optimal advantage while performing tasks. Furthermore, this has clinical and educational implications for children with ADHD that are discussed in detail in section 4.3 – Educational and Clinical Implications for ADHD.

4.1 Possible Influences and Mechanisms of Feedback on Error Processing

The present study found that feedback had the expected effect of enhancing accuracy and post-error adjustment in typically developing children. For controls, just pointing out their errors was enough for them to do something about it and led them to reduce the total number of errors made. Unlike controls, children with ADHD had difficulty using knowledge of results to significantly enhance their post-error adjustment and task accuracy. As mentioned previously, even in the Feedback condition, children with ADHD did not even display post-error adjustment or accuracy at the levels that controls participants did in the No Feedback condition.

One possible influence of feedback on the control groups’ post-error adjustment may be that every single error was detected by participants, as the provision of feedback reduced or eliminated the need to self-detect errors, thereby enhancing error detection. The detection phase of error processing likely does not require conscious detection (Ullsperger, & von Cramon,
2003); however, conscious detection of results may in fact lead to greater salience of the result (Hughes & Yeung, 2011). If this is the case, then in the No Feedback condition participants may not have been consciously aware of their results, perhaps leading to less salience associated with the result, and less effect on error processing. In fact, past research on cognitive tasks of error processing have shown that external feedback elicits ERNs in individuals similar to those generated when depending solely on the self-detection of errors (Ullsperger, & von Cramon, 2003; Miltner, Braun, & Coles, 1997; Luu et al., 2003). Interestingly, other studies that have found that Pe (a wave generated after an ERN wave), was only present for conscious, rather than unconscious errors (Hughes & Yeung, 2011; Nieuwenhuis et al., 2001). Therefore, more errors may have been consciously detected in the Feedback condition, increasing post-error adjustment across groups.

Alternatively, feedback may have also had a rewarding or reinforcing effect that impacted task performance and post-error adjustment. In order to understand how the feedback used in the present study may possess such reinforcing qualities, psychological, cognitive and neural theories of reward are considered.

Berridge et al. (2009) parsed the psychological features of reward into components of “liking” and “wanting.” A reward is considered to be something that is desired as it can produce the affect or emotion of implicit “liking” and/or a conscious experience of subjective pleasure. Berridge et al. (2009) refers to this component of reward as “liking” and that an individual “wants” or desires a reward that they “like.” The term “wanting” is meant to describe the implicit incentive salience that comes with rewards, a type of motivation that encourages approaching and experiencing rewards and that can lead to cognitive goals. Furthermore, a task, an object, and so on, can acquire “wanting,” or incentive salience, or motivational properties,
when it is paired with the receipt of an innate reward (i.e., associated with something “liked”). In the case of the present paradigm and feedback employed, it is possible that the innate “liking” of being correct, (or perhaps “dislike” of making errors, as incentive salience may also share neurobiological underpinnings with fear salience), created or increased task saliency and participants’ motivation as reflected by increased post-error adjustment and accuracy in the Feedback condition. Negative feedback in particular (i.e., errors) may have also increased saliency through increasing participants’ anxiety, leading them to slow down after errors because they were anxious or fearful of making another error.

In addition to salience, inherent in reward paradigms is also the psychological component of learning, which may include the explicit and implicit knowledge formed by associative conditioning and cognitive processes (Berridge & Robinson, 2003). In the feedback condition of the modified flanker tasks used, reinforced learning (via “liking” and “wanting”) may have occurred when particular responses were reinforced with a correct feedback signal. The reinforcement pathway in the brain that is associated with dopaminergic function is thought to be aberrant in children with ADHD, which may explain both this groups’ error processing deficit and why they did not respond in the Feedback condition the way typically developing children did. In fact, feedback has been shown to be both knowledge of results and reward (Stauffer, Lak, Kobayashi, & Schultz, 2015). Therefore, when feedback is given, a correct response could be viewed as a reward and an error as an aversive stimulus. Furthermore, dopaminergic neurons are highly responsive to rewards as well as to aversive stimuli (Stauffer et al., 2015). Dopaminergic neurons also code the subjective value of a reward/aversive stimulus and the amount of activity in these neurons parallels the magnitude of the subjective value and salience placed on a reward/aversive stimulus (Stauffer et al., 2015). Feedback as a reward/aversive stimulus could
therefore act by increasing subjective value and salience, thereby increasing dopaminergic neuronal activity, and leading to residual neuronal activity that can act to change plasticity and update the top-down dopaminergic network involved in reinforcement learning (Stauffer et al., 2015). In the case of the present study, it was found that feedback improved post-error adjustments and accuracy in typically developing children who are presumed to have intact reinforcement learning. This result makes sense because feedback enhances saliency and therefore the dopaminergic networks underlying reinforcement learning. However, given that this is the very mechanism that appears to be disrupted in ADHD, children with ADHD do not benefit from enhancing the saliency of errors, as this relies on the atypical dopaminergic networks found in ADHD.

In fact, research has indicated that children with ADHD can be unusually responsive to reward salience as mediated in part by the midbrain dopamine system (Holroyd et al., 2008). Furthermore, decreased function in the dopamine reward pathway has also been found in adults with ADHD, and has been hypothesized to underlie some of the motivational deficits in ADHD (Volkow et al., 2011). Many studies have shown that cognitive performance in children with ADHD is affected by reward and that several cognitive deficits associated with the disorder may even be attenuated with reward. Research on adults with ADHD showed improved performance on several executive functioning tasks when participants were provided with monetary reward (Marx, Höpcke, Berger, Wandschner, & Herpertz, 2013). A study using a flanker task with and without performance-based rewards found that children with ADHD had enhanced Pe amplitude when provided with rewards (Rosch & Hawk, 2013). Given the psychological, cognitive and neural account of feedback as reward, it is possible that children with ADHD did not find the feedback provided in this study as salient or rewarding as controls did (Groom et al.,
2013; Holroyd, Baker, Kerns, & Muller, 2008; Rosch & Hawk, 2013). Additionally, children with ADHD may require different types of feedback or require higher levels of saliency, reward, or motivation than what was provided in the present study.

Direct observations of the ADHD group used in this study when completing the modified flanker tasks indicated that they were often quite vocal and animated in their disappointment at receiving a low tone signal which indicated an error, and equally enthused about receiving a high tone signal indicating a correct response. However, as posited in the current study, children with ADHD demonstrated an error processing deficit with this feedback, no matter how much that feedback drove detection/adjustment processes, or how rewarding or salient that feedback was, it still did not normalize their deficit. This again suggests that atypical dopaminergic networks regulate the error processing deficit in ADHD.

In addition to the possible influences of feedback already discussed, there are several other factors that may also affect adjustment. These potential influences are considered below.

4.2 Other Factors that may Influence Adjustment

Task reaction times, and therefore adjustment, can be influenced by several cognitive processes. Therefore, alternative reaction time explanations for adjustment must be considered. Reaction times were examined to ensure that any differences in adjustment were not accounted for by the overall speed or variability of responding, as ADHD participants have been observed to have greater variability across cognitive tasks (Andreou et al., 2007). Results revealed that the mean reaction time on correct and incorrect trials, and their variability was not significantly different between groups. As such, the possibility that the differences observed between groups
on post-error adjustment was due to significantly slower reaction times overall in the control group, or from significantly variable reaction times in the ADHD group, were ruled out.

Similarly, as performance monitoring is hypothesized to play a significant role in learning (Tam et al., 2013; Ullsperger, 2010) and previous research has shown that children with learning disabilities (both reading disability alone, and math and reading disabilities together), but no ADHD have atypical error processing (Burgio-Murphy et al., 2007; Shafrir, Siegel, & Chee, 1990), it is possible that the children with ADHD who have comorbid learning disabilities (LD) are accounting for the observed group differences. However, when the comorbid ADHD and LD subgroup was excluded from analyses, the results remained significant (in fact, they became even more robust), indicating that the possible contribution of weak error processing in children with ADHD and comorbid LD did not account for the group differences obtained. This finding suggests that the deficit in error processing observed in the present study is more closely related to a diagnosis of ADHD.

Age was found to correlate with post-correct adjustment across groups and conditions, but not with post-error adjustment. It was found that older children, regardless of ADHD status, displayed (on average) more post-correct speeding compared to younger children across conditions. Given the strong relationship between post-correct speeding and task accuracy found in the present study, it is possible that older children were able to begin the task at an appropriate fast-accurate reaction time band, thereby not needing to greatly adjust their reaction time after correct responses in order to meet task demands. As a corollary of this, younger children may have not had as keen a sense (given lack of experience) of where to begin their reaction time band, thereby requiring greater shifts in their reaction time after correct responses in order to meet task demands. Alternatively, older children were able to reach an optimum fast-accurate
reaction time band following correct responses over fewer trials compared to younger children, who may have required more trials to fine tune their post-correct adjustment over the task.

When the effects of age were controlled for, the findings of the present study remained significant. Research investigating the effect of age on performance monitoring has been stimulated by a developmental model which posits that it does not reach adult levels until late adolescence (Davies, Segalowitz, & Gavin, 2004). Therefore, this suggests that performance monitoring would improve as one develops and ages. While the current results support this notion of development in regards to performance monitoring of correct responses, there was no correlation between age and error processing. It is possible that a larger age range or a greater number of older participants was required to find any possible age effects on post-error adjustment in the present study. A study aimed at exploring the development of error processing using a modified flanker task also found no significant differences between the ages of 7 to 9 (Richardson, Anderson, Reid, & Fox, 2011), but this result was found in a limited age range.

Gender was not a significant factor in adjustment across groups and conditions. In addition, the three ADHD subtypes as defined by the DSM-IV (inattentive subtype, hyperactive/impulsive subtype, and combined subtype) were compared on dependent variables. Results indicated no significant difference between any of the subtypes on adjustment or accuracy, suggesting that individuals with ADHD exhibited similar performance regardless of subtype classification. These findings are consistent with results from other studies revealing no differences in performance among ADHD subtypes on other executive function tasks (Schachar et al., 2005; Oosterlaan et al., 2005; Oosterlaan, Logan, & Sergeant, 1998). In contrast, one study found impaired post-error adjustment on a choice discrimination task only for children with the ADHD-Inattentive subtype (Shiels et al., 2012). The authors argue their findings
highlight the importance of considering task demands and ADHD subtype when examining adjustment.

ADHD symptom severity and impairment as rated by parents and teachers, and clinician rated impairment, was also not related to adjustment, suggesting that greater symptoms or impairment resulting from ADHD does not impact adjustment. This finding supports the notion of ADHD as a categorical rather than quantitative trait, especially in relation to cognitive deficits associated with the disorder. Furthermore, no significant relationship was found between full scale IQ and adjustment. Performance on a measure of working memory (i.e., digit span subtest of the WISC-IV) was also examined for its relationship with adjustment. Results revealed no significant relationship between this working memory measure and adjustment.

The finding that working memory is not related to adjustment is interesting given that cognitive accounts of error processing posit that updating of working memory is required in order to use errors to adjust one’s behaviour (Holroyd & Coles, 2002; Shiels & Hawk, 2010). Similarly, research has indicated that children with ADHD possess deficits in their working memory (Martinussen, et al., 2005). It is possible that the limited working memory measures available in the present study (i.e., digit span backwards and forwards subtests of the WISC-IV) are not as extensive, or perhaps as sensitive, as is required in order to capture any possible relationship between adjustment and working memory. It is also plausible that error processing and working memory deficits in ADHD are separable, suggesting that the combination of the two deficits would likely be very detrimental.

Overall, the relationship between a post-error adjustment deficit and ADHD appears to be specific as age, gender, IQ, working memory, ADHD subtype, symptom severity, and impairment did not significantly impact on this relationship.
4.3 Educational and Clinical Implications for ADHD

Academic measures were examined for their relationship with adjustment. Typically developing children showed no significant relationships between adjustment and academic measures. However, the ADHD group displayed a significant positive correlation between post-correct adjustment across conditions and performance on word reading, spelling, and math achievement scores.

This is an interesting result as it was found that post-correct speeding in children with ADHD (and controls) was associated greater flanker task accuracy, but was associated with lower scores on measures of academic performance. This discrepancy may speak to the complexity of academic measures that are dependent on many external factors such as previous learning and experience. Given that these relationships were not found in controls, it is possible that children with ADHD perform better on academic tasks when they slow down after giving correct responses. Perhaps slowing down in general is a more adaptive adjustment for those with an ADHD diagnosis when they are performing academic tasks because of their greater hyperactive and impulsive symptoms. On the other hand, no correlations were found between academic measures and post-error adjustment in the control or ADHD group. This again suggests the complexity of academic measures, or that slowing following an error in academic tasks does not always enhance performance. Likely, there is an optimal amount of task-specific slowing or speeding after making a response that is not too slow (so as to ensure efficient completion), and not too fast (so as to ensure accurate completion; i.e., akin to a “goldilocks” scenario). The consequence of task-specific optimal adjustments may be that adjustment is not generalizable across tasks, especially with complex tasks such as academic measures that also require a significant amount of previous learning and experience. Given this consideration,
future research aimed at determining the association between performance monitoring and academic measures may benefit from using timed academic achievement tests, such as the Math Fluency Subtest of the Woodcock-Johnson Tests of Achievement (WJ-ACH-III; Woodcock, Shrank, McGrew, & Mather; 2005). Such timed tests (if computerized) would allow for an accurate measurement of adjustment after making errors and correct responses on an academic measure, thereby elucidating the relationship between performance monitoring and academic achievement (in this case math).

It is important to note that the present study did not involve measures of learning, rather only academic achievement. Therefore, these findings may be the result of a difference between fluid and crystalized problem solving/reasoning skills (i.e., fluid reasoning is the capacity to solve novel problems independent of acquired knowledge, whereas crystallized problem-solving is the ability to use already acquired skills, knowledge, and experience). Learning tasks tap into fluid reasoning as they relates to novel material, whereas academic achievement taps into crystalized problem-solving as it relates to already learned information. It is possible that once tasks transition from fluid to crystalized reasoning skills they do not depend as much on performance monitoring abilities. While the present results allow for speculation about learning, as achievement can suggest learning, the relationships found are only with academic achievement measures and not with true learning tasks.

Even though there were no correlations between post-error adjustment and the academic measures available, the error processing deficit found in the current study suggests that learning from errors may be an area of difficulty for children with ADHD. Learning from errors often forms the basis of educational teaching and clinical work with children with ADHD. The finding that they are not able to adjust their performance following errors is important to understanding
the learning and behavioural profiles of these children. While the results obtained in a controlled laboratory setting are not always generalizable to other settings, it is plausible that under certain conditions, this deficit may impact daily functioning and in particular, impair learning and achievement within an educational context.

The present results indicate that for children with ADHD, parents and teachers should not expect that just pointing out errors will change or enhance any subsequent performance. Rather, these children may need to be instructed on what strategies/knowledge to use once they have made an error, or how to implement strategies/knowledge that they already possess. It will be relevant for parents and educators to question if children with ADHD have the requisite strategies/knowledge required to adjust their behaviour appropriately after making an error. That is, do they know and understand what to do after making an error? Alternatively, even if children with ADHD are aware of what strategies to employ, perhaps they have difficulty with implementation of this strategy, and as a result do not adjust their behaviour accordingly. That is, are children with ADHD able to take the appropriate steps necessary, even if they know what those steps are? Exploring these questions is an area of future research that can help shape possible interventions aimed at improving this deficit in ADHD. For example, a version of the flanker task could be employed to determine this, where children are provided with explicit instruction on how to adjust to errors, that is “slow down after you make a mistake.” If children with ADHD continue to show atypical adjustment, then it is not attributable to not knowing what to do, rather it is because they are have difficulty implementing that knowledge and strategy.

From a clinical perspective, the present findings also support the notion that error processing is cognitive deficit of ADHD. In fact, Gupta and Kar (2010) argue for the inclusion of error processing as a likely cognitive impairment of ADHD. Furthermore, cognitive-
behavioural and behavioural therapy, both of which draw on reinforcement learning principles and self-monitoring techniques, are thought to be effective in generating and maintaining improvement in the behaviour of children with ADHD. Cognitive-behavioural therapies tend to focus on providing alternative ways of cognitive problem-solving and on direct reinforcement of certain behaviours. However, behaviour modification programs for children with ADHD that are implemented by parents and educators do not always provide direct instruction to children on how to actively monitor their behaviour for errors and most importantly, what strategies to use and how to apply them appropriately following an error. These programs instead focus on reinforcing a behaviour, which increases the chances that the behaviour will reoccur; however, it does not necessarily provide a child with strategies for success when they make mistakes. Introducing such strategies along with reinforcement could be especially beneficial for children with ADHD.

Despite children with ADHD’s struggle to learn effectively from errors, it appears that they may learn well from success as they displayed similar post-correct adjustment to controls in the present study. This suggests that when children with ADHD are having success through their knowledge, strategy use, or implementation on a task, they are likely to continue to succeed on that task. This promotes the use of “errorless learning” techniques with children diagnosed with ADHD. Errorless learning tends to be emphasized in areas where accurate task completion may be more closely linked to motivation, emotions or behaviour and not necessarily to competency or skill set. This reflects the difference between a child knowing a strategy or how to accomplish a task and adjusting their behaviour accordingly (with presumed motivation), versus a child not wanting to comply with requests or tasks, not out of a lack of competency, but rather due to emotions, behaviour, or other obstacles. As such, errorless learning paradigms have been
developed to address obstacles to learning that go beyond a lack of knowledge or competency. Errorless compliance training is one such intervention that is success-based, non-coercive, and non-intrusive, and is often used with children who have severe oppositional behavior (Ducharme, Atkinson, & Poulton, 2000). The success of such interventions suggests that an errorless approach is well suited to managing motivational, emotional and behavioural difficulties in children. However, errorless interventions can also be easily paired with competency training as may often be required.

In summary, the results of the current study indicate that children with ADHD have difficulty making adjustments following errors and therefore likely struggle to learn from their mistakes. These results support teaching children with ADHD about task-specific post-error strategies and their implementation after making an error. A detailed discussion of the limitations of Study 1 and possible areas of future research are included in Chapter 9 – Limitations and Future Research.
5. Chapter 5 - Study 2 Introduction

The results of Study 1 indicate an error processing deficit in children with ADHD. Given the highly heritable nature of ADHD (Banerjee, Middleton, & Faraone, 2007), it is plausible that this deficit may reflect familial genetic or environmental components. If familiality of error processing ability is discovered within ADHD, this would support its use as a marker of genetic risk (i.e., an endophenotype) in ADHD. In order to examine this in Study 2, a brief description of endophenotypes in general and as they relate to ADHD is necessary.

5.1 Endophenotypes

Endophenotypes can be defined as heritable traits that can indicate an individual’s liability to develop or manifest a given disease, serving as a marker of genetic risk (Rommelse, 2008). Importantly, endophenotypes are proposed to be intermediaries between the genotype and phenotype of a disorder. Therefore, endophenotypes are generally anatomical, neurochemical, neurophysiological, or cognitive traits. Fundamental to endophenotypes is the assumption that they are putatively closer to gene action than are phenotypes, and/or are influenced by fewer genes than phenotypes, hence providing greater power for genetic and other biological analyses (Bellgrove, O’Connell, & Vance, 2008). The main objectives for incorporating endophenotypes into genetic studies of psychiatric disorders are to understand the mechanism of action of known risk genes and to discover new risk genes for a disorder. Therefore, to be useful, endophenotypes should be specific, quantifiable, and objective measures of a disorder that are less susceptible to the potential inconsistencies or bias in clinical phenotypes, symptom categories, and diagnoses. Additional advantages of studying endophenotypes, in addition to phenotypes, are that endophenotypes can often be more
objectively (and therefore more reliably) measured compared to phenotypes. Furthermore, while an endophenotype is present in affected individuals, it can also be observed in unaffected first-degree relatives of an affected individual, since they are likely to share some of the susceptibility genes of a disorder. Therefore, one part to establishing traits as endophenotypes is to look for them in first-degree relatives, pointing to the importance of family studies of endophenotypes.

### 5.2 Sibling Studies of ADHD

Family studies have become essential to the assessment of endophenotypes in order to establish the familiality of an endophenotype through its presence in unaffected biological relatives of an affected individual. One of the most common family studies used with disorders of childhood are sibling studies as these can reduce the potential effects of age and developmental experience on task performance.

Ma, Roberts, Winefield, and Furber (2015) conducted a systematic review of sibling studies of mental health disorders over the past twenty years and found that the greatest elevated risk of psychopathology was found in siblings of children with ADHD compared to any other mental health disorder. Prevalence rates of ADHD in siblings of children with ADHD range from 18 to 29 % (Ma, Roberts, Winefield, & Furber, 2015). Furthermore, studies show that siblings of children with ADHD have significantly higher odds (1.9 to 4.6 times higher) of being diagnosed with ADHD than do control siblings (Ma et al., 2015). These findings point to ADHD having more heritable or shared environmental risks than other disorders. In fact, siblings of children with ADHD also had similarly greater odds of having CD/ODD, affective disorders, and anxiety disorders compared to control siblings (Ma et al., 2015). This suggests that ADHD may also have more heritable or shared environmental risks with other mental health disorders.
Sibling studies of executive functioning in ADHD have found consistent results that indicate both the familiality of deficits in ADHD, and intermediate deficits across several executive functions in unaffected siblings. For example, individuals with ADHD and their unaffected siblings have demonstrated impairments relative to controls on inhibitory control, reaction time variability, attentional control, and mental flexibility (Albrecht et al., 2013; Schachar et al., 2005). Furthermore, impairment in unaffected siblings was found to be an intermediate deficit between that of children with ADHD and controls.

To date, only two studies have investigated error processing in the unaffected siblings of children with ADHD. These studies examined ERP indices of error processing during a flanker task in ADHD participants, unaffected siblings, and controls (Albrecht et al., 2008; Albrecht et al., 2010). ERP indices indicated an ERN and conflict monitoring deficit (i.e., reduced N2 amplitude enhancement arising from conflicting or incongruent flankers) in children with ADHD, and an intermediate deficit in unaffected siblings. The authors contend that both deficits are related to dopaminergically modulated functions of the anterior cingulate cortex (ACC), and that these deficits may well constitute an endophenotype of ADHD. It is important to note that these studies have only examined ERP indices and not behavioural indices of error processing. Given the greater feasibility and scalability of behavioural measures, future research will need to consider behavioural indices of error processing in sibling studies.

A putative mechanism for intermediate deficits in unaffected siblings has been proposed (Morein-zamir, Simon Jones, Bullmore, Robbins, & Ersche, 2013). Siblings may show an intermediate deficit for phenotypes influenced by shared genetic factors because either: (1) As full biological siblings share on average 50% of their genes, any deficit will be found in some but not all siblings, and therefore as a group they will show 50% of the deficit (i.e., some siblings
share more deficit related genes and have more of the deficit, whereas other siblings share fewer
deficit related genes and have less of the deficit), or (2) siblings share much of the genetic risk
for the deficit, but have protective factors (that are either biological, non-shared environmental,
or an interaction of genes and environment), that are able to compensate for the existing genetic
vulnerability leading away from a total phenotypic manifestation of the deficit, and instead
resulting in a partial or attenuated deficit.

Overall, the sibling studies of executive functioning and error processing in ADHD have
found consistent results supporting the familiality of deficits in ADHD, with unaffected siblings
showing intermediate deficits. However, it is important to note that although a trait may be
familial it does not ensure that it is also heritable as shared environmental factors can also
generate familial similarity (Crosbie, Perusse, Barr, & Schachar, 2008). Twin and adoption
studies are required to determine genetic heritability.

5.3 Endophenotypes of ADHD

The heritability (i.e., the percentage of variance between individuals on a particular trait
that is due to genetic influences) of ADHD is substantial. Studies on the heritability of ADHD
have found large genetic influences, irrespective of the choice of instrument, informant, or
gender and age of the individual (Derks, Hudziak, & Boomsma, 2009). Across many studies, the
heritability of ADHD has been found to range between 35% to 89% (Derks et al., 2009). Many
twin and adoption studies have also highlighted the highly heritable nature of ADHD, with the
mean heritability of ADHD shown to be 77% (Banerjee et al., 2007), and behavioral studies in
ADHD suggest a heritability of approximately 76% (Coghill & Banaschewski, 2009). Even
across differing clinical definitions of ADHD - it being viewed as part of a continuum (i.e., best
viewed as the extreme of a behavior that varies throughout the entire population), or viewed as a
categorical disorder with various symptom cut-offs - heritability rates of 75% to 91% were
found, and remained robust across familial relationships (i.e., twins, siblings, and twin–sibling
pairs) (Levy, Hay, McStephen, Wood, & Waldman, 1997). Furthermore, the results of a recent
study examining clinically diagnosed ADHD across the lifespan revealed a high heritability of
ADHD of 88% (with a 95% confidence interval of 83% – 92%) across a large age sample of
children, adolescents, and adults (Larsson, Chang, D'Onofrio, & Lichtenstein, 2014).

There is also strong familiality in ADHD as the disorder has been found to be elevated in
first-degree relatives of individuals with ADHD (American Psychiatric Association, 2013).
Most studies assessing genetic risk factors in ADHD support the strong familial nature of
ADHD, with family studies identifying a 2 to 8-fold increase in risk for ADHD among parents
and siblings of children with ADHD (Banerjee et al., 2007).

Notwithstanding the high heritability and familiality of ADHD, there are many
environmental risk factors and potential gene-environment interactions that also increase risk for
the disorder. Several biological and environmental factors have been proposed as risk factors for
ADHD, including food additives, diet, lead contamination, cigarette and alcohol exposure,
maternal smoking during pregnancy, and low birth weight (Banerjee et al., 2007). Research has
also emphasized the role of psychosocial factors in maintaining, exacerbating, or improving the
impairments associated with ADHD (Larsson et al., 2014).

Despite the high heritability of ADHD, it has been difficult to find genetic factors
conferring risk. This difficulty arises from etiological heterogeneity (which is common to most
mental health disorders) and weak genetic methods to date. The present consensus is that there
may be multiple etiological pathways from genes to phenotype, each one of which involves a
different subset of cognitive processes and behavioural manifestations (Smalley, McCracken, & McGough, 2001). Results of genetic studies of ADHD are complicated by the heterogeneity of these etiological pathways and may also vary as a consequence of the instrument(s) or informant(s) used to assess ADHD. Therefore, genetic studies of ADHD would benefit from endophenotypes that reflect intermediaries between the genotype and phenotype of a disorder, bringing genetic analyses closer to genes compared to standard phenotypes (Smalley et al., 2001).

With this goal in mind, recent research in psychopathology and ADHD has turned to determining endophenotypes. Despite the findings of previous studies indicating that the majority of the variance in ADHD symptoms is due to genetic factors, genome wide association studies (GWAS) of ADHD have not yet identified replicable associations that can account for this heritable variation (Wood & Neale, 2010). As such, endophenotypes are of great interest in ADHD research because it has been suggested that the power to detect genetic associations can be improved by the study of heritable endophenotypes. Regardless of whether the genetic variation underlying ADHD is polygenic, or the result of multiple private mutations or rare variants, endophenotypes can help specify traits researchers can examine in genetic studies in order to discern which genetic pathways are affected that in turn lead to ADHD.

Crosbie, Perusse, Barr, and Schachar (2008) proposed a priori criteria by which candidate endophenotypes of ADHD should be selected and validated before they are applied to genetic research. Briefly, these criteria include the following: (1) Sensitivity and specificity: An endophenotype should be common in affected individuals (i.e., sensitive), and relatively, if not completely, unique to the disorder (i.e., specific). However, such specificity does not mean that an endophenotype cannot be found in other disorders as shared genetic risks may contribute to an endophenotype that interacts differently with each person’s environment, leading to divergent
behavioural outcomes and phenotypes. This potential of shared genetic risk with other disorders may contribute to the elevated risk of comorbidity noted in ADHD. “In such cases, the specificity of an endophenotype would not be high although it might still increase power for detecting genetic risks for each disorder” (Crosbie et al., 2008). (2) Heritability: Endophenotypes should be heritable, meaning that the endophenotypic variation in the population should be partly caused by genetic variation between individuals. (3) Familial aggregation: An endophenotype should be evident in some relatives of affected individuals. (4) Presence in unaffected family members: A corollary of familial aggregation is that an endophenotype should be present even in the unaffected relatives of affected individuals. (5) State-independence: A valid endophenotype will not vary with disease progression or treatment (unless this affects the endophenotype) and will not vary with measurement technique. (6) Genetic mediation/biological plausibility: A genetically mediated relationship between an endophenotype and the disorder is a vital feature of a putative endophenotype. (7) Sound psychometric properties: Candidate endophenotypes should be reliable if they reflect enduring traits. Standardized measures would be particularly helpful, especially if the endophenotype varies with age or gender in a systematic way, as is likely to be the case for cognitive processes. (8) Feasibility: Candidate endophenotypes should be easy to measure and non-invasive in order to facilitate large-scale research in affected individuals, their relatives and the general population.

While most candidate endophenotypes in ADHD have not yet been validated using these criteria, “the most common endophenotypes under consideration in ADHD are neuropsychological measures of executive function, although a range of psychological, physiological and neuroanatomical endophenotypes have been proposed” (Crosbie et al., 2008). Given the impairments found in ADHD, many of the proposed endophenotypes to date have
been deficient executive functioning. Executive functions lend themselves to their use as endophenotypes given the ease by which they can be measured, and their heritability even within the general populations. In fact, a twin study of three executive functions (response inhibition, working memory, and shifting task sets), indicated that while these executive functions were highly correlated because they are influenced by an extremely heritable (99%) common factor (beyond just general intelligence or perceptual speed), they were also separable because of additional genetic influences that are unique to each executive function (Friedman et al., 2008). This combination of general and specific genetic influences places executive functions among the most heritable psychological traits and support their use as possible endophenotypes in psychopathology (Friedman et al., 2008).

Several of the executive functions that have been proposed as potential endophenotypes for ADHD include: sustained attention, verbal and visuospatial working memory (Bellgrove et al., 2008), reaction time variability (Andreou et al., 2007), abnormality in reward-related cognition (Castellanos & Tannock, 2002), and deficits in time estimation (Rommelse et al., 2008). The most validated candidate endophenotype in ADHD is inhibitory control, also known as response inhibition (Bellgrove et al., 2008).

5.4 Error Processing as a Candidate Endophenotype of ADHD

Error processing is an important executive function and as shown in Study 1, children with ADHD display a deficit in it. Error processing as a candidate endophenotype of ADHD has not been adequately evaluated using behavioural measures and family studies. However, a few studies have examined genetic and familial influences on ERP indices of error processing. One such study administered a flanker task and found that healthy adolescent (aged 12) monozygotic
and dizygotic twins had substantial heritability (40 to 60%) on their ERP indices of error processing (Anokhin, Golosheykin, & Heath, 2008). Other research examining the familiality of error processing in ADHD found that ERP indices related to error processing on a flanker task were deficient in ADHD families compared to healthy families, and familial within a sample of ADHD participants and unaffected siblings of children with ADHD (Albrecht et al., 2008; Albrecht et al., 2010).

Other research investigated whether polymorphisms in the DAT1 and DRD4 gene led to inter-individual differences within a normal population on ERP indices of error processing on a modified flanker task (Biehl et al., 2011). This research was based on neural models of error processing that hypothesize the involvement of the brain’s dopaminergic system. Researchers found effects of the DAT1 and DRD4 genotype on ERP indices of error processing. These findings associate error processing to dopaminergic genotypes, supporting a link between atypical error processing in ADHD and theoretical models of abnormal dopaminergic neurotransmission in ADHD. Further support for the prominent role of dopamine in error processing is found in a review of genetic association studies of error processing that surveyed electroencephalogram (EEG), neuroimaging, and computational modeling studies assessing polymorphisms of candidate genes affecting dopaminergic neurotransmission (Ullsperger, 2010b). Given the putative role of dopamine in error processing, if error processing is found to be familial, it would likely serve as a beneficial endophenotype in genetics studies of dopamine in ADHD.

Some studies have proposed the use of ERP indices as candidate endophenotypes for psychopathology associated with the abnormal regulation of behavior (Anokhin et al., 2008), concluding that these neural markers do meet several important criteria as endophenotypes.
These criteria include heritability, established neuroanatomical and neurochemical substrates, association with neuropsychiatric disorders, presence in unaffected family members, and evidence of genetic mediation (Manoach & Agam, 2013). In ADHD in particular, research has also proposed the use of ERP indices of error processing as possible endophenotypes (Tye, McLoughlin, Kuntsi, & Asherson, 2011). Despite these findings, the use of ERP indices of error processing as an endophenotype are significantly limited by their feasibility of use (which typically involves attaching several electrodes, or a full net of electrodes, to a subject’s head, requiring an array of specialized equipment and technicians). In comparison, a behavioral measure of error processing is both feasible (only requiring a computer software program), and scalable in large-scale research.

In regards to studies investigating the genetic and familial influences on the behavioural indices of error processing, there has been only one study to date which examined post-error adjustment. The study explored genetic influences on post-error adjustment in a sample of healthy adults to determine if individual differences in post-error adjustment were related to differences in a genetic polymorphism (a variation in a gene associated with the production of an enzyme that catalyzes the conversion of dopamine to norepinephrine) (Colzato, de Rover, van den Wildenberg, & Nieuwenhuis, 2013). It was observed that individual differences in post-error adjustment on a Simon task were predicted by differences in this genetic polymorphism. This research is a first step to using behavioural indices of error processing as endophenotypes in genetic research.
5.5 Study 2 Aims and Hypotheses

Study 1 indicated that children with ADHD display atypical error processing. These findings lead to an examination of whether or not error processing (as was studied in Study 1) is familial. Given the putative genetic basis of error processing, if error processing is found to be familial, it may serve as a beneficial endophenotype in genetics studies of ADHD. Therefore, in the context of a sibling study, Study 2 aims to determine whether error processing meets the familial criterion of an endophenotype of ADHD. More specifically, Study 2 aims to determine the familiality of adjustment following errors in ADHD. Adjustment following errors will be indexed by the behavioural measure of post-error adjustment, with deficient post-error adjustment operationalized as less post-error adjustment than controls (also referred to as typically developing children). The same modified flanker task (Eriksen & Eriksen, 1974) and task conditions used in Study 1 will also be employed in Study 2. A sibling study methodology will be utilized with controls, children with ADHD, and unaffected siblings of children with ADHD (Albrecht et al., 2008).

I predict that children with ADHD will demonstrate a deficit in post-error adjustment (i.e. less post-error adjustment than controls), thereby confirming the deficit reported in Study 1. I also hypothesize that unaffected siblings of children with ADHD will show deficient post-error adjustment that is intermediate between that of children ADHD and controls, thereby indicating familiality of the post-error adjustment deficit. As a corollary of this, given that post-error adjustment was shown to be highly related to task accuracy in Study 1, I predict that there will also be a significant difference in task accuracy across groups, with controls demonstrating greater accuracy. I also postulate that in line with the results of Study 1, children with ADHD will show post-correct adjustment similar to controls, and therefore based on the presumed
familiality of adjustment, unaffected siblings will also show post-correct adjustment that is similar to controls, suggesting that the deficit is related to error processing and not to performance monitoring in general.

Due to the methodological issues that arise from sibling studies examining mental health difficulties, Ma et al. (2015) suggested a list of guidelines for future research to follow that encourage methodologically robust studies. The present study has met these guidelines, which include obtaining all data on siblings and affected individuals, obtaining data from multiple informants, using multiple measures, combining all of this data, and using structured diagnostic interviews and standardized measures.

Similarly to Study 1, the secondary research questions of any potential relationships between adjustment and accuracy, sample characteristics (i.e., response speed, age, IQ, or gender), working memory, and learning (i.e., measures of academic achievement and examining the comorbid learning disability group), will be addressed. As in Study 1, I hypothesize that adjustment and scholastic achievement will not be significantly related in the present study because achievement scores are proxies of learning and not true learning tasks. I also predict that a significant relationship will be found between adjustment and working memory because cognitive theories suggest that updating of working memory is required in order to use errors to adjust one’s behaviour. Furthermore, I posit that greater accuracy will be significantly related to greater adjustment because it is adaptive to adjust one’s behaviour. Lastly, I hypothesize that the sample characteristics assessed will not account for group differences in adjustment because previous research has indicated a deficit in performance monitoring in children with ADHD independent of these variables (Schachar et al., 2004).
6. Chapter 6 - Study 2 Method

All procedures used with participants in Study 1 are identical in Study 2. Similarly, all measures, task conditions, and dependent variables are identical to those described in Study 1. Therefore, only the participants and statistical procedures used in Study 2 differ from Study 1 and are described below.

6.1 Participants

A subset of ADHD and control (or typically developing) participants from Study 1 were used in Study 2. ADHD and unaffected sibling participants were specifically recruited for a “sibling study of ADHD.” Therefore, a subset of the ADHD participants from Study 1 who were recruited for the “sibling study of ADHD” and met the inclusion and exclusion criteria outlined below were also included in Study 2. Children with ADHD and unaffected siblings of children with ADHD were drawn from referrals to a clinic specializing in children with attention, learning and behaviour problems in a large urban pediatric hospital. Typically developing children from Study 1 who met the inclusion and exclusion criteria outlined below were also included in Study 2. These control participants were recruited through advertisement within the hospital.

Only those participants from Study 1 who had a full biological sibling were included in Study 2 in order to control for any genetic or environmental factors associated with having siblings, and children with ADHD were only included if they and their biological sibling also participated in our research. In Study 2, 100% of the controls and the children with ADHD were from drawn from Study 1. However, Study 2 added a new group of unaffected siblings of children with ADHD who received the same rigorous assessment as children with ADHD, but did not meet criteria for ADHD.
All participants ranged in age from 6 to 16 years of age and were attending a primary or secondary school, ensuring that both a parent and a teacher could serve as informants. The sample was drawn from communities surrounding the hospital, yielding participants who were likely representative of the ethnicity and socioeconomic status of the communities from which they were drawn. All children were required to be free of psychotropic medication for at least 24 hours prior to testing because of potential impact of medications on adjustment or task accuracy (Barnes et al., 2014; Groom et al., 2013).

The same diagnostic, cognitive, psychoeducational, language, and social-emotional functioning assessment procedures as those described in Study 1 were employed for both controls and children with ADHD. Unaffected siblings of children with ADHD received an identical diagnostic, cognitive, psychoeducational, language, and social-emotional functioning assessment to that of children with ADHD.

For children with ADHD and unaffected siblings of children with ADHD, all of the measures and information gathered were used by a clinical team composed of a psychiatrist, psychologist, social worker/nurse, and speech language pathologist to determine any clinical diagnoses including ADHD, oppositional defiant disorder, conduct disorder, depression, separation anxiety, generalized anxiety, and learning disability.

6.1.1 Inclusion Criteria

Participants with at least one full biological sibling were drawn from clinic and control samples in order to control for any genetic or environmental factors associated with having siblings. To be classified as ADHD for research purposes, children had to meet DSM-IV-TR criteria for ADHD (American Psychiatric Association, 2000) defined as at least 6 of 9
inattentive, 6 of 9 hyperactive/impulsive symptoms, or both. To ensure that children were at least moderately impaired in two settings as per DSM-IV-TR, it was required that they met criteria for ADHD from the parent or the teacher interview and questionnaires, and a minimum of 4 ADHD symptoms were reported according to the second informant, with a “moderately impaired” rating on both the parent and teacher impairment scales.

Unaffected siblings were included in this study if they did not meet DSM-IV-TR criteria for ADHD (as determined by the clinical team based on parent and teacher interviews, rating scales and questionnaires), but at least one of their sibling(s) did meet criteria for ADHD.

Control participants were included in this study if they did not meet DSM-IV-TR criteria for ADHD on the parent or teacher Conners’ Rating Scales (Conners, 1997) defined as obtaining T-Scores less than 60 on the DSM-IV Inattentive, DSM-IV Hyperactive-Impulsive, and DSM-IV Total subscales. Typically developing children were also included if no other behavioural, psychiatric, hearing, language, or learning problems were endorsed on the OCHS scales (Boyle et al., 1993), or on the self-report measures of the MASC (March et al., 1997) and CDI (Kovacs, 1985).

6.1.2 Exclusion Criteria

Participants were excluded if they fulfilled any of the following criteria: (a) Full Scale IQ below 80, (b) presence of a serious medical condition, substance abuse, a history of traumatic brain injury from parent-reported history (c) concurrent treatment with medication other than a stimulant, (d) specific language impairment (as defined by a CELF total language score was below 85) as it may interfere with assessment and cognitive testing, or (e) hearing or visual impairment. Fourteen ADHD participants were excluded due to language impairment and 2 due
to low IQ from the 45 cases of ADHD probands. No unaffected siblings were excluded from the 26 cases assessed.

Control participants were excluded from this study if they obtained T-Scores greater than or equal to 60 on the DSM-IV Inattentive, DSM-IV Hyperactive-Impulsive, or DSM-IV Total subscales of the parent or teacher Conners’ Rating Scales (Conners, 1997) thereby meeting criteria for ADHD. Typically developing children were also excluded if any other behavioural, psychiatric, hearing, language or learning problems were endorsed on the OCHS scales (Boyle et al., 1993), or on the self-report measures of the MASC (March et al., 1997) and CDI (Kovacs, 1985). Using these criteria no control participants were excluded in the present study from the 28 assessed.

Outliers, defined as scores + or – 3 standard deviations from the mean of the dependent measures of post-correct or post-error adjustment in either condition, were excluded from all analyses. This excluded one control, one unaffected sibling, and two ADHD participants.

After applying all inclusion and exclusion criteria, there were a total of 27 typically developing children (controls), 25 unaffected siblings, and 34 children with ADHD who participated in this study.

6.2 Analyses

The list of dependent variables analyzed in Study 2 is found in Table 1. In order to evaluate the effects of group membership and feedback on adjustment after errors and correct responses and on task accuracy, a mixed design Multivariate Analysis of Variance (MANOVA) was conducted with the between-subjects factor being group membership (i.e., ADHD, Unaffected Siblings, and Controls), and the within-subjects factor being condition (i.e., No Feedback vs.
Feedback). In order to protect against inflated Type 1 error rates, if the MANOVA was non-significant (i.e., the null hypothesis was true), then no further tests were performed. Significant MANOVAs were followed up by a post-hoc mixed design Univariate Analyses of Variance (ANOVA) on each dependent variable. Adjustment was correlated with age, gender, task accuracy, symptom severity, impairment, academic and working memory measures. In order to address secondary research questions or particular results, follow-up and covariate analyses were conducted where appropriate.
7. Chapter 7 - Study 2 Results

Assumptions of normality and homogeneity of variance were not violated in the following analyses. No participant had 100% accuracy which would have precluded analysis of post-error adjustment, and no participant had accuracy of less than 40% which would have suggested near random responding.

7.1 Sample Characteristics

Sample characteristics can be found in Table 7 below. Groups did not significantly differ in age ($F(2,85) = 0.42, \text{n.s.}$), but were significantly different on IQ ($F(2,84) = 19.7, p < .000$). Bonferroni post-hoc tests revealed that controls displayed significantly greater IQ than both the unaffected sibling ($p = .004$) and the ADHD groups ($p < .000$). Unaffected siblings displayed significantly greater IQ than children with ADHD ($p < .027$). There was a significant difference between groups on their gender proportions ($\chi^2 (2) = 17.68, p < .000$). The groups also significantly differed on word reading scores (WRMT-R Single Word Reading Standard Scores; $F(2,85) = 11.3, p < .000$). Bonferroni post-hoc tests revealed that controls displayed significantly greater word reading scores than the ADHD group ($p < .000$), but not the unaffected sibling group ($p = .185$). Unaffected siblings displayed significantly greater word reading scores than children with ADHD ($p = .033$). Similarly, groups significantly differed on a measure of reading comprehension (WRAT-III Reading Comprehension Standard Score; $F(2,50) = 9.1, p < .000$). Bonferroni post-hoc tests revealed that controls displayed significantly greater reading comprehension scores than the ADHD ($p < .000$) and the unaffected sibling groups ($p = .049$). Unaffected siblings displayed similar reading comprehension scores to children with ADHD ($p = .476$). On a measure of spelling groups also showed significant differences (WRAT-III Spelling
Standard Score; \( F(2,64) = 11.3, p < .000 \). Bonferroni post-hoc tests revealed that controls displayed significantly greater spelling scores than the ADHD group \( (p < .000) \), but not the unaffected sibling \( (p = 1.00) \). Unaffected siblings displayed significantly greater spelling scores than children with ADHD \( (p < .005) \). Groups showed significant differences on math achievement scores (WRAT-III Arithmetic Standard Score; \( F(2,83) = 6.3, p < .003 \)). Bonferroni post-hoc tests revealed that controls displayed significantly greater math scores than the ADHD group \( (p < .002) \), but not the unaffected sibling \( (p = .378) \). Unaffected siblings displayed similar math scores to children with ADHD \( (p = .20) \).

The groups displayed significant differences on the Conners’ Parent Rating Scale DSM-IV: Total Subscale T-Score \( (F(2,86) = 59.7, p < .000) \) and Conners’ Teacher Rating Scale DSM-IV: Total Subscale T-Score \( (F(1,86) = 34.8, p < .000) \). Bonferroni post-hoc tests revealed that controls displayed significantly lower T-Scores than the ADHD group (Conners’ Parent Rating Scale: \( p < .000 \); Conners’ Teacher Rating Scale: \( p < .000 \)), but not the unaffected sibling group (Conners’ Parent Rating Scale: \( p = .230 \); Conners’ Teacher Rating Scale: \( p = .274 \)). Similar to typically developing children, unaffected siblings also displayed significantly lower T-Scores than children with ADHD (Conners’ Parent Rating Scale: \( p < .000 \); Conners’ Teacher Rating Scale: \( p < .000 \)). The unaffected sibling group also showed significantly less impairment as rated by parents and teachers (OCHS Scaled Score; \( F(1,57) = 28.8, p < .000 \), and by clinicians (on CGAS scores whereby greater impairment is denoted by lower scores; \( F(1,50) = 56.9, p < .000 \), as well as significantly less parent and teacher rated symptom severity (PICS-IV and TTI-IV Summary Scores; \( F(1,54) = 125.2, p < .000 \) than the ADHD group.
Table 7

**Summary of Sample Characteristics for Study 2**

<table>
<thead>
<tr>
<th></th>
<th>Control (N = 27)</th>
<th>Unaffected Siblings (N = 25)</th>
<th>ADHD (N = 34)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demographics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>Male 30% Female 70%</td>
<td>Male 64% Female 36%</td>
<td>Male 82% Female 18%</td>
</tr>
<tr>
<td>Age (years)</td>
<td>Mean 10.1 SD 3.3</td>
<td>Mean 9.8 SD 2.2</td>
<td>Mean 9.5 SD 1.9</td>
</tr>
<tr>
<td>**Academic/</td>
<td>Mean 118.1 SD 11.2</td>
<td>Mean 108.1 SD 10.4</td>
<td>Mean 100.6 SD 10.7</td>
</tr>
<tr>
<td>Psychoeducational</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measures**</td>
<td>Mean 113.3 SD 11.2</td>
<td>Mean 106.4 SD 14.0</td>
<td>Mean 97.4 SD 13.9</td>
</tr>
<tr>
<td>IQ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Word Reading</td>
<td>Mean 114.4 SD 9.2</td>
<td>Mean 105.8 SD 9.7</td>
<td>Mean 100.9 SD 10.1</td>
</tr>
<tr>
<td>Standard Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(WRMT-R)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reading Comprehension</td>
<td>Mean 111.2 SD 12.9</td>
<td>Mean 107.7 SD 16.6</td>
<td>Mean 93.0 SD 13.1</td>
</tr>
<tr>
<td>Standard Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(WRAT-III)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arithmetic Standard</td>
<td>Mean 106.0 SD 15.4</td>
<td>Mean 100.3 SD 11.8</td>
<td>Mean 93.8 SD 12.1</td>
</tr>
<tr>
<td>Score (WRAT-III)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digit Span Forwards</td>
<td>Mean 12.2 SD 3.1</td>
<td>Mean 10.3 SD 3.3</td>
<td>Mean 8.8 SD 2.7</td>
</tr>
<tr>
<td>Scaled Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(WISC-IV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digit Span Backwards</td>
<td>Mean 11.7 SD 3.2</td>
<td>Mean 11.3 SD 3.0</td>
<td>Mean 9.3 SD 3.0</td>
</tr>
<tr>
<td>Scaled Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(WISC-IV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Clinical Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conners’ Parent</td>
<td>Mean 46.9 SD 5.2</td>
<td>Mean 51.4 SD 10.7</td>
<td>Mean 70.9 SD 9.9</td>
</tr>
<tr>
<td>Rating Scale DSM-IV:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Subscale (T-Score)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conners’ Teacher</td>
<td>Mean 47.2 SD 5.7</td>
<td>Mean 51.9 SD 12.0</td>
<td>Mean 67.2 SD 7.6</td>
</tr>
<tr>
<td>Rating Scale DSM-IV:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Subscale (T-Score)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parent and Teacher</td>
<td>Mean 5.0 SD 4.9</td>
<td>Mean 20.5 SD 5.1</td>
<td></td>
</tr>
<tr>
<td>Rated Symptom</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severity Summary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Score (PICS-IV and TTI-IV)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The sample of children with ADHD and unaffected siblings were composed of a heterogeneous group with associated or comorbid diagnoses typical of clinic samples (please see Table 8).

Table 8

Diagnoses in ADHD and Unaffected Sibling Samples for Study 2

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of Participants (N)</th>
<th>Percentage of Participants (%)</th>
<th>Diagnoses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaffected Siblings 1</td>
<td>1</td>
<td>4%</td>
<td>Learning Disability</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>8%</td>
<td>Separation Anxiety</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>12%</td>
<td>Oppositional Defiant Disorder (ODD)</td>
</tr>
<tr>
<td>18</td>
<td>18</td>
<td>72%</td>
<td>None</td>
</tr>
<tr>
<td>ADHD</td>
<td>15</td>
<td>44%</td>
<td>ADHD – Combined Type</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
<td>41%</td>
<td>ADHD – Inattentive Type</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>15%</td>
<td>ADHD – Hyperactive/Impulsive Type</td>
</tr>
</tbody>
</table>

Subtype:

ADHD – Combined Type
ADHD – Inattentive Type
ADHD – Hyperactive/Impulsive Type

Comorbid Diagnoses:

<table>
<thead>
<tr>
<th>Number of Participants (N)</th>
<th>Percentage of Participants (%)</th>
<th>Diagnoses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3%</td>
<td>Non-Verbal Learning Disability</td>
</tr>
<tr>
<td>1</td>
<td>3%</td>
<td>Depression</td>
</tr>
<tr>
<td>1</td>
<td>3%</td>
<td>Pervasive Developmental Disorder (PDD)</td>
</tr>
<tr>
<td>4</td>
<td>3%</td>
<td>Autism</td>
</tr>
<tr>
<td>4</td>
<td>12%</td>
<td>Generalized Anxiety (GAD)</td>
</tr>
<tr>
<td>5</td>
<td>12%</td>
<td>Learning Disability</td>
</tr>
<tr>
<td>5</td>
<td>14%</td>
<td>Oppositional Defiant Disorder (ODD)</td>
</tr>
<tr>
<td>17</td>
<td>50%</td>
<td>None</td>
</tr>
</tbody>
</table>

Analyses were performed with and without the 3 participants diagnosed with PDD or Autism, yielding the same significant results. Therefore, these 3 participants were included in the analysis.
7.2 Main and Interaction Effects

Means and standard deviations for all dependent variables are listed in Table 9. Results of a mixed design MANOVA indicated a significant multivariate interaction of group and condition across all dependent variables ($F(6,162) = 2.76, p < .015$). Follow-up post-hoc univariate ANOVA analyses were conducted on each dependent variable and are listed in Table 10.

No significant interaction or main effect of group or condition was found on post-correct adjustment (see Figure 5). A significant interaction between group and condition on post-error adjustment was found ($F(1, 83) = 3.64, p < .035$; see Figure 6). A significant interaction between group and condition on task accuracy was also found ($F(1, 83) = 3.98, p < .025$; see Figure 7). These results indicate that the Feedback condition had a differential effect on post-error adjustment and accuracy in each group. To determine how each group was differentially affected, tests of simple effects were conducted to examine these significant interactions more closely. Only controls showed a significant increase in their post-error adjustment (Controls: $F(1, 83) = 11.86, p = .001$; Unaffected Siblings: $F(1, 83) = 0.06, n.s.$; ADHD: $F(1, 83) = 0.59, n.s.$) and task accuracy (Controls: $F(1, 83) = 8.55, p = .004$; Unaffected Siblings: $F(1, 83) = 0.52, n.s.$; ADHD: $F(1, 83) = 0.07, n.s.$) in the Feedback condition compared to the No Feedback condition. Additionally, only in the Feedback condition did controls show greater post-error adjustment (Controls vs. Unaffected Siblings: $p = .008$; Controls vs. ADHD: $p = .007$) and task accuracy (Controls vs. Unaffected Siblings: $p = .004$; Controls vs. ADHD: $p = .001$) than the other groups. The unaffected sibling and ADHD groups were not significantly different from one another on post-error adjustment (Unaffected Siblings vs. ADHD: $p = .889$), or task accuracy (Unaffected Siblings vs. ADHD: $p = .816$).
Overall, these results indicate a significant effect of performance feedback on adjustment following an error and task accuracy in the control group. When provided with knowledge of results, controls adjusted their behaviour by significantly slowing their reaction time after making errors and increased task accuracy, whereas unaffected siblings and children with a diagnosis of ADHD did not. The unaffected sibling and ADHD groups also did not significantly differ from one another on these measures.

Table 9

*Means and Standard Deviations of Dependent Variables*

<table>
<thead>
<tr>
<th></th>
<th>Controls</th>
<th>Unaffected Siblings</th>
<th>ADHD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>No Feedback Condition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Correct Adjustment (ms)</td>
<td>-0.8</td>
<td>33.3</td>
<td>4.2</td>
</tr>
<tr>
<td>Post-Error Adjustment (ms)</td>
<td>28.9</td>
<td>153.6</td>
<td>30.8</td>
</tr>
<tr>
<td>Accuracy (percent correct)</td>
<td>80.1</td>
<td>12.6</td>
<td>77.6</td>
</tr>
<tr>
<td>Feedback Condition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Correct Adjustment (ms)</td>
<td>-13.1</td>
<td>24.1</td>
<td>-2.1</td>
</tr>
<tr>
<td>Post-Error Adjustment (ms)</td>
<td>126.4</td>
<td>161.4</td>
<td>23.9</td>
</tr>
<tr>
<td>Accuracy (percent correct)</td>
<td>86.7</td>
<td>8.4</td>
<td>75.9</td>
</tr>
</tbody>
</table>

Table 10

*Univariate ANOVA Post-Hoc Results*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Main Effect of Group</th>
<th>Main Effect of Condition</th>
<th>Interaction of Group and Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-value  p-value</td>
<td>Effect Size (η²)</td>
<td>F-value  p-value</td>
</tr>
<tr>
<td>Post-Correct Adjustment (ms)</td>
<td>1.04</td>
<td>.360</td>
<td>.024</td>
</tr>
<tr>
<td>Post-Error Adjustment (ms)</td>
<td>3.62</td>
<td>.031*</td>
<td>.080</td>
</tr>
<tr>
<td>Accuracy (percent correct)</td>
<td>2.30</td>
<td>.107</td>
<td>.052</td>
</tr>
</tbody>
</table>

*Note.* * indicates significance at the 0.05 level.
Figure 5. Post-correct adjustment in milliseconds (ms) in Study 2

Figure 6. Post-error adjustment in milliseconds (ms) in Study 2
There was no significant main effect or interaction of condition or group on post-correct adjustment indicating no significant differences between children with ADHD, unaffected siblings, and controls across conditions on post-correct adjustment.

This significant interaction of group and condition on post-error adjustment reveals that the Feedback condition caused a significant post-error adjustment of slowing in the control group, but not in the unaffected sibling or ADHD groups. Tests of simple effects revealed that controls, but not unaffected siblings or children with ADHD, showed significantly different post-error adjustment across conditions. There were only significant group differences in the Feedback condition, but not in the No Feedback condition. The unaffected sibling and ADHD groups did not significantly differ from each other on this measure.

This significant interaction of group and condition on task accuracy reveals that the Feedback condition was associated with a significant increase in accuracy for the control group, but not for the unaffected sibling or ADHD groups. Tests of simple effects revealed that only controls showed significantly greater accuracy across conditions. There were significant group differences in the Feedback condition, but not the No Feedback condition. The unaffected sibling and ADHD groups did not significantly differ from each other on this measure.

**7.3 Correlates of Adjustment**

There was no significant relationship between age or full scale IQ and post-correct or post-error adjustment across conditions (see Table 11). Within the unaffected sibling group only, less post-error adjustment was correlated with greater parent and teacher rated impairment ($r(25) = -.41, p < .05$). Within the ADHD group, symptom severity (i.e., the total number of
ADHD symptoms reported by parents and teachers combined, and impairment (both parent and teacher reported measures of impairment obtained from the OCHS Scales (Boyle et al., 1993) and clinician rated measures of impairment on the Children’s Global Assessment Scale (CGAS; Shaffer, Gould, Bird, et al., 2000), did not correlate with adjustment across conditions.

For both conditions, a highly significant relationship was found between accuracy and adjustment across groups. Increased accuracy was related to less post-correct adjustment (No Feedback: $r(86) = -.29, p = .008$; Feedback: $r(86)= -.36, p = .001$), and related to greater post-error adjustment (No Feedback: $r(86) = .34, p = .001$; Feedback: $r(89)= .43, p < .0005$) across groups. Further analyses were conducted to determine if adjustment was related to accuracy in other measures (for correlations see Table 11). In the control and unaffected sibling groups, adjustment was not correlated with any academic or working memory measures. In the ADHD group, results revealed a significant positive correlation between post-correct adjustment across conditions and performance on word reading (WRMT-R Word Identification Subtest; Woodcock, 1987). However, spelling (WRAT-III Spelling Subtest; Wilkinson, 1993), math (WRAT-III Arithmetic Subtest; Wilkinson, 1993), reading comprehension (WRAT-III Global Reading Score; Wilkinson, 1993), and working memory (i.e., digit span forwards and backwards standard scores on the WISC-IV; Wechsler, 2003) measures were not significantly related to adjustment in the ADHD group across conditions.
### Table 11

**Correlates of Adjustment in Study 2**

<table>
<thead>
<tr>
<th>Across Groups</th>
<th>Post-Correct Adjustment</th>
<th>Post-Error Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demographics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>r(89) = -.17, p-value = .112</td>
<td>r(89) = .06, p-value = .609</td>
</tr>
<tr>
<td>Accuracy</td>
<td>No Feedback: r(89) = -.29, p-value = .008*</td>
<td>No Feedback: r(89) = .34, p-value = .001**</td>
</tr>
<tr>
<td></td>
<td>Feedback: r(89) = -.36, p-value = .001**</td>
<td>Feedback: r(89) = .43, p-value = &lt; .0005***</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Controls</th>
<th>Academic/Psychoeducational Measures</th>
<th>r(27)</th>
<th>p-value</th>
<th>r(27)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full Scale IQ (WASI)</td>
<td>.24</td>
<td>.230</td>
<td>-.08</td>
<td>.697</td>
</tr>
<tr>
<td></td>
<td>Single Word Reading (WRMT-R)</td>
<td>-.05</td>
<td>.825</td>
<td>-.12</td>
<td>.561</td>
</tr>
<tr>
<td></td>
<td>Reading Comprehension (WRAT-III)</td>
<td>-.08</td>
<td>.759</td>
<td>.09</td>
<td>.733</td>
</tr>
<tr>
<td></td>
<td>Spelling (WRAT-III)</td>
<td>-.03</td>
<td>.890</td>
<td>-.02</td>
<td>.921</td>
</tr>
<tr>
<td></td>
<td>Arithmetic (WRAT-III)</td>
<td>-.14</td>
<td>.496</td>
<td>.05</td>
<td>.804</td>
</tr>
<tr>
<td></td>
<td>Digit Span Forwards (WISC-IV)</td>
<td>-.44</td>
<td>.060</td>
<td>.20</td>
<td>.422</td>
</tr>
<tr>
<td></td>
<td>Digit Span Backwards (WISC-IV)</td>
<td>-.33</td>
<td>.172</td>
<td>.09</td>
<td>.718</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unaffected Siblings</th>
<th>Academic/Psychoeducational Measures</th>
<th>r(25)</th>
<th>p-value</th>
<th>r(25)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full Scale IQ (WISC-IV)</td>
<td>-.04</td>
<td>.862</td>
<td>.13</td>
<td>.532</td>
</tr>
<tr>
<td></td>
<td>Single Word Reading (WRMT-R)</td>
<td>.19</td>
<td>.372</td>
<td>.02</td>
<td>.918</td>
</tr>
<tr>
<td></td>
<td>Reading Comprehension (WRAT-III)</td>
<td>.22</td>
<td>.456</td>
<td>-.01</td>
<td>.971</td>
</tr>
<tr>
<td></td>
<td>Spelling (WRAT-III)</td>
<td>-.18</td>
<td>.500</td>
<td>-.11</td>
<td>.557</td>
</tr>
<tr>
<td></td>
<td>Arithmetic (WRAT-III)</td>
<td>.25</td>
<td>.223</td>
<td>-.34</td>
<td>.097</td>
</tr>
<tr>
<td></td>
<td>Digit Span Forwards (WISC-IV)</td>
<td>-.10</td>
<td>.650</td>
<td>.006</td>
<td>.979</td>
</tr>
<tr>
<td></td>
<td>Digit Span Backwards (WISC-IV)</td>
<td>-.06</td>
<td>.780</td>
<td>-.10</td>
<td>.631</td>
</tr>
</tbody>
</table>
### Clinical Measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>$r$</th>
<th>$p$-value</th>
<th>$r$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent and Teacher Rated Symptom Severity</td>
<td>.10</td>
<td>.670</td>
<td>-.15</td>
<td>.516</td>
</tr>
<tr>
<td>(PICS-IV and TTI-IV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parent and Teacher Rated Impairment (OCHS)</td>
<td>.13</td>
<td>.538</td>
<td>-.41</td>
<td>.042*</td>
</tr>
<tr>
<td>Clinician Rated Impairment (CGAS)</td>
<td>-.11</td>
<td>.630</td>
<td>.27</td>
<td>.220</td>
</tr>
</tbody>
</table>

### ADHD

<table>
<thead>
<tr>
<th>Academic/Psychoeducational Measures</th>
<th>$r$</th>
<th>$p$-value</th>
<th>$r$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Scale IQ (WISC-IV)</td>
<td>.19</td>
<td>.281</td>
<td>.10</td>
<td>.577</td>
</tr>
<tr>
<td>Single Word Reading (WRMT-R)</td>
<td>.38</td>
<td>.026*</td>
<td>-.19</td>
<td>.282</td>
</tr>
<tr>
<td>Reading Comprehension (WRAT-III)</td>
<td>.28</td>
<td>.243</td>
<td>-.26</td>
<td>.280</td>
</tr>
<tr>
<td>Spelling (WRAT-III)</td>
<td>.18</td>
<td>.394</td>
<td>.02</td>
<td>.945</td>
</tr>
<tr>
<td>Arithmetic (WRAT-III)</td>
<td>.22</td>
<td>.216</td>
<td>.18</td>
<td>.308</td>
</tr>
<tr>
<td>Digit Span Forwards (WISC-IV)</td>
<td>.03</td>
<td>.853</td>
<td>.02</td>
<td>.904</td>
</tr>
<tr>
<td>Digit Span Backwards (WISC-IV)</td>
<td>.07</td>
<td>.692</td>
<td>.11</td>
<td>.553</td>
</tr>
</tbody>
</table>

### Clinical Measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>$r$</th>
<th>$p$-value</th>
<th>$r$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent and Teacher Rated Symptom Severity</td>
<td>.03</td>
<td>.853</td>
<td>.06</td>
<td>.748</td>
</tr>
<tr>
<td>(PICS-IV and TTI-IV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parent and Teacher Rated Impairment (OCHS)</td>
<td>-.32</td>
<td>.065</td>
<td>.20</td>
<td>.256</td>
</tr>
<tr>
<td>Clinician Rated Impairment (CGAS)</td>
<td>-.06</td>
<td>.766</td>
<td>-.06</td>
<td>.762</td>
</tr>
</tbody>
</table>

*Note.* *indicates significance at the 0.05 level, **indicates significance at the 0.005 level, *** indicates significance at the 0.0005 level.

### 7.4 Secondary Analyses

In order to determine that the differences found in adjustment were not a function of differences in overall reaction times or reaction time variability, a follow-up univariate analysis was conducted examining the reaction times of the groups. Results revealed that the mean
reaction time on correct \( (F(1,83) = 3.06, \text{n.s.}) \) and incorrect trials \( (F(1,83) = 2.33, \text{n.s.}) \), and their variability (Correct Response Time Variability: \( F(1,83) = 2.85, \text{n.s.} \); Incorrect Response Time Variability: \( F(1,83) = 2.64, \text{n.s.} \)) was not significantly different between groups.

There were 2 participants in the unaffected sibling group with a learning disability (LD; 1 with a math disability and 1 with a reading disability), and 7 participants in the ADHD group with comorbid LD (1 with comorbid ADHD and math disability, and 4 with comorbid ADHD and reading disability). Unaffected siblings with a LD and children with ADHD and comorbid LD were removed from their respective groups. The remaining participants without any LD were compared to controls on dependent variables using a mixed design MANOVA. There remained a significant multivariate interaction of group and condition on across all dependent variables \( (F(6,150) = 2.32, p < .04) \). Post-hoc univariate ANOVA results revealed that post-correct adjustment \( (F(2,76) = 1.17, \text{n.s.}) \) remained similar across groups. Post-error adjustment \( (F(2,76) = 4.38, p < .02) \) and task accuracy \( (F(1,76) = 2.53, p < .01) \) remained significantly different between groups across conditions. Unaffected siblings \( (p = .004) \) and ADHD participants \( (p = .001) \) continued to show significantly less post-error adjustment than controls in the Feedback condition. Furthermore, unaffected siblings \( (p = .004) \) and ADHD participants \( (p = .012) \) also showed significantly less task accuracy than controls in the Feedback condition.

To examine any potential differences between genders on adjustment, follow-up t-tests comparing males to females across groups on post-correct and post-error adjustment across conditions were conducted. Results revealed that post-correct adjustment \( (t(84) = 2.55, p < .015) \) and post-error adjustment \( (t(84) = 3.34, p = .001) \) were significantly different between genders. Girls displayed greater post-correct speeding and post-error slowing across conditions and groups compared to boys. A mixed design MANCOVA indicated that once gender was
controlled for, with the exception of the results on task accuracy, the previous results of the study remained significant. There remained a significant multivariate interaction of group and condition across all dependent variables \(F(6,162) = 2.32, p < .04\). Post-hoc univariate ANCOVA analyses when gender was controlled for indicated no significant interaction or main effect of group or condition on post-correct adjustment. A significant interaction between group and condition on post-error adjustment was again found \(F(2, 82) = 4.02, p < .025\). Within the Feedback condition, unaffected siblings \(p = .016\) and ADHD participants \(p = .015\) continued to show significantly less post-error adjustment than controls, and unaffected siblings and children with ADHD did not differ \(p = .997\). However, when gender was controlled for, there was no longer a significant interaction or main effect of condition or group on task accuracy \(F(2, 82) = 2.44, n.s.\). Results also indicated that controls were again the only group that enhanced both accuracy \(p < .025\) and post-error adjustment \(p = .001\) in the Feedback condition compared to the No Feedback condition.
8. Chapter 8 - Study 2 Discussion

The present study aimed to determine the potential familiality of error processing in ADHD. A sibling study methodology was utilized in order to investigate the presence of any error processing deficit in unaffected siblings of children with ADHD. In order to examine error processing, a task paradigm (the modified flanker task; Eriksen & Eriksen, 1974) was chosen that elicits both correct responses and errors in the same task, evokes adjustment in the form of post-correct and post-error adjustment, is amenable to feedback manipulation, and has task accuracy benefits when adjustment is employed.

8.1 Familiality of Error Processing in ADHD

In addition to the results indicating that children with ADHD demonstrate a post-error adjustment deficit and less accuracy than controls, what is notable about the results of Study 2 is that the unaffected sibling group also displayed a deficit and accuracy similar to that of children with ADHD. The present results indicate that unaffected siblings, while not clinically expressing ADHD themselves, do exhibit deficits in error processing which supports the familiality of atypical error processing in ADHD. It is important to note that not only are the unaffected siblings in this study not diagnosed with ADHD, but they are also not “sub-threshold” for an ADHD diagnosis. Therefore, the significant difference found in post-error adjustment and accuracy between unaffected siblings and controls cannot be attributed to sub-threshold ADHD symptoms or related impairment in unaffected siblings (i.e., unaffected siblings do not significantly differ from typically developing children on ADHD symptom severity or parent, teacher, and clinician rated impairment associated with ADHD symptoms). Moreover,
unaffected siblings present significantly less ADHD symptoms and related impairment than children in the ADHD group despite showing similarly atypical error processing.

While this finding clearly suggests a familial deficit, from the results of this study alone it cannot be determined if the familial association is genetic or environmental, or an interaction of both (only a twin study can determine that). While this result could be an effect of shared environment, it is important to note that shared environment is more than psychosocial; it can be biological as well (such as exposure to toxins). However, little variance in twin studies of ADHD is environmental (Banerjee et al., 2007), and where it is environmental, it is often found to be a non-shared environmental effect (i.e., environmental effects that make siblings different, not similar). Therefore, this supports a genetic interpretation of the familiality found in the present study, even in absence of twin studies.

It is also considered if this result is an epiphenomenon of ADHD (i.e., a phenomenon that occurs simultaneously with a disease or condition and therefore usually results in correlations with symptoms, whereas genetically mediated phenomena often do not correlate with symptomatology). The present findings do not point to the deficit being an epiphenomenon of ADHD because it occurred in unaffected siblings who do not have ADHD, and there were no significant correlations between ADHD symptom scores and adjustment.

Interestingly, results did not support the hypothesis that the unaffected sibling deficit would be intermediate between that of children with ADHD and typically developing children. Rather, it was found that unaffected siblings demonstrated a similar magnitude of impairment as children with ADHD. The notion that unaffected siblings would show intermediate deficits is predicated on the belief that full biological siblings sharing 50% of their genes on average, and that error processing is likely the result of multiple gene interactions that are additive. However,
this finding does not conform to this notion of polygenic etiology of error processing, but instead may suggest evidence of the action of some specific set of risks (i.e., specific shared genetic risks that are fully penetrant at the cognitive but not at the behavioral level in unaffected siblings, or a shared environmental risk that confers, or interacts with shared genes to confer poor error processing in unaffected siblings).

Typically developing children, those with ADHD, and unaffected siblings all displayed similar post-correct adjustment across conditions. These findings suggest that correct performance monitoring is a relative strength in children with ADHD and their unaffected siblings.

As in Study 1, the feedback provided did not normalize the observed deficit. In fact, with respect to task accuracy, the ADHD and unaffected sibling groups actually performed slightly better on average in the No Feedback condition over the Feedback condition. It is possible that the salience of the error and correct signals in the Feedback condition actually hampered the unaffected sibling and ADHD groups’ performance by placing more emphasis on being accurate (Holroyd et al., 2008). However, the Feedback condition did not hinder the control group as they showed significantly increased accuracy and post-error adjustment. Unlike the present results, another study involving children with ADHD and unaffected siblings found that incentives (i.e., winning and losing points on a task and trading these in for a prize) positively affected performance on a go/no-go task in both children with ADHD and unaffected siblings (Uebel et al., 2010). This study and others have suggested familial motivational dysfunction in ADHD (Uebel et al., 2010; Volkow et al., 2011). It is plausible then that compared to controls, children with ADHD and unaffected siblings require (actual or perceived) greater, more salient, or more
rewarding feedback or incentives. An in-depth discussion of the possible influence of feedback on post-error adjustment among children with ADHD and controls can be found in Study 1.

Taken together, the present results support the familiality of the error processing deficit in ADHD. Unaffected siblings perform more similarly to children with ADHD than to control participants who do not have a sibling with ADHD. This may point to an increased genetic loading of ADHD risk genes that influence error processing abilities in unaffected siblings of children with ADHD. In addition to these findings, there are several other factors that may also influence post-error adjustment and must be considered. These possible influences are discussed below.

**8.2 Other Factors that may Influence Adjustment**

Task reaction times, and therefore adjustment, can be influenced by several cognitive processes. Therefore, alternative reaction time explanations for adjustment must be considered. Reaction times were examined to ensure that any differences in adjustment were not accounted for by the overall speed or variability of responding correctly or incorrectly. Not only have ADHD participants been observed to have greater variability across cognitive tasks, but variability has also been proposed as an endophenotype of ADHD; however the specificity and sensitivity of this trait is not yet known and no biological mechanism has been clearly proposed (Andreou et al., 2007). Results revealed that the mean reaction time on correct and incorrect trials, and their variability was not significantly different between groups. As such, the possibility that the differences observed between groups on post-error adjustment was a function of significantly slower reaction times overall in the control group, or from significantly variable reaction times in the unaffected sibling or ADHD group, were ruled out.
Similarly, as performance monitoring is hypothesized to play a significant role in learning (Tam et al., 2013; Ullsperger, 2010a) and previous research has shown that children with learning disabilities (both reading disability alone, and math and reading disabilities together) but no ADHD have atypical error processing (Burgio-Murphy et al., 2007; Shafrir, Siegel, & Chee, 1990), it is possible that unaffected siblings with a learning disability (LD) and children with ADHD who have comorbid LD are accounting for the observed group differences. However, when the unaffected siblings and ADHD participants with an LD were excluded from analyses, the results remained significant, indicating that the possible contribution of weak error processing in children with LDs did not account for the group differences obtained. This finding suggests that the deficit in error processing observed in the present study is more closely related to a diagnosis of ADHD.

The present study did not find age or IQ to be associated with post-error adjustment across groups or conditions. For a discussion on age and development in relation to post-error adjustment, please refer to Study 1 Discussion. The lack of association of post-error adjustment and IQ in unaffected siblings is consistent with previous research. For example, Wood et al. (2011) found that IQ did not account for the observed deficit on measures of executive functioning (i.e., (four-choice reaction time task, a go/no-go task, and choice-delay task) in unaffected siblings of children with ADHD.

Results revealed that post-correct and post-error adjustment were significantly different between genders. Girls displayed more adaptive adjustments after both errors and correct responses than boys. When gender was controlled for, controls continued to show significantly enhanced post-error adjustment than both the unaffected siblings and ADHD groups, and unaffected siblings and children with ADHD continued display a similar post-error adjustment.
deficit. However, with gender controlled for, group differences on task accuracy were no longer significant suggesting that gender accounted for some of the variance observed in task accuracy. Despite this lack of significant differences, when gender was covaried the estimated marginal means of task accuracy across conditions still indicated that controls ($M = 81.0$) had greater task accuracy on average than unaffected siblings ($M = 77.0$) and children with ADHD ($M = 78.4$).

A diagnosis of ADHD is 2 to 9 times more likely to occur in boys than girls, and clinic referred children are more likely to be male (American Psychiatric Association, 2000). Furthermore, in the present study there were many more females in the control group compared to both the unaffected sibling and ADHD groups. Therefore, the relationship between gender and adjustment may be an artifact of the gender distribution inherent in the groups examined, with controls having more girls, and ADHD and unaffected sibling groups being largely composed of boys. There is very limited research on the impact of gender on adjustment as only one study has examined possible gender influences on the familiality of error processing (Albrecht et al., 2010). This study assessed unaffected children with a family history of ADHD and controls, and confirmed that familial deficits in error processing were independent of gender. Another study that examined sustained attention and inhibitory control in ADHD also found that the effects of gender were independent of familial effects, which in turn suggests that familiality of executive function deficits are independent of gender (Uebel et al., 2010).

Less post-error adjustment was correlated with greater parent and teacher rated impairment in the unaffected sibling group, but not in the ADHD group. This result may speak to the psychopathological significance of error processing. While the current study did not find a relationship between adjustment and impairment or severity in the ADHD group, one study has found such a relationship. Schachar et al. (2004) found that less post-error adjustment was
significantly correlated with greater ADHD severity, suggesting that children with greater severity associated with ADHD also adjusted the least following errors. Combined, these results suggest that there may be a psychopathological effect of the error processing deficit; however, such possible effect(s) on symptoms, severity and impairment require further investigation.

Similarly to Study 1, no associations between post-error adjustment and academic or working memory measures were found. Please refer to Study 1 for a discussion of this finding. Also seen in Study 1, a positive correlation between word reading and post-correct adjustment in the ADHD group was found. Typically developing children and unaffected siblings showed no significant relationships between post-correct adjustment and academic or working memory measures. A detailed discussion of the clinical and educational implications of these findings can be found in Study 1.

### 8.3 Error Processing: A Candidate Endophenotype of ADHD

The present study has found familiality of a post-error adjustment deficit, a component of error processing, within unaffected siblings of children with ADHD. This result lends support to the use of error processing as an endophenotype of ADHD. Assuming that the error processing deficit in unaffected siblings of children with ADHD is genetically mediated (as is proposed above), then the extent of the unaffected siblings’ deficit found suggests that this trait has the ability to detect either: (1) asymptomatic genetic carriers of the trait (i.e., unaffected siblings have the same genes that cause error processing deficits, but do not possess other ADHD disease causing genes making them asymptomatic), or (2) those with incomplete penetrance of the ADHD causing genotype (i.e., unaffected siblings have the same ADHD disease causing genes, but they do not fully manifest in the same disease phenotype due to other biological or
environmental factors), or (3) those with compensatory/protective mechanisms for existing
genetic vulnerabilities that steer away from the phenotypic manifestation of ADHD (i.e.,
unaffected siblings have some or all of the same ADHD disease causing genes, but they do not
manifest in the same disease phenotype due to compensatory/protective factors).

Once additional research further validates error processing as an established
endophenotype of ADHD, the next step will be to link this trait to genetic variants in ADHD
populations (Goos, Crosbie, Payne, & Schachar, 2009). A detailed discussion of the limitations
of the present study and possible areas of future for research are included in the chapter below.
9. Chapter 9 – Limitations and Future Research

While a discussion of the specific findings of each study has already been presented, it is also important to also consider the limitations of the current studies and the implications of their results on future research.

A potential limitation of the present research is that because ADHD, like most neurodevelopmental disorders, is very heterogeneous in terms of subtypes and is compounded by comorbidity, there are many sample characteristics that must be considered. By including many of these varying sample characteristics in the ADHD sample, such as subtype and comorbidity, an attempt was made to have a sample that was representative of the ADHD population; however, these sample characteristics may have impacted the results of the studies. In the case of the sample characteristics of age, gender, learning disability comorbidity, ADHD subtype, symptom severity and impairment, analyses were conducted to ensure that this was not the case. Similarly, studies are often limited by their sample sizes and this may have been the case in the present research. However, the sample sizes used in both studies did possess enough statistical power to find robust group differences in error processing and were large enough to allow for the examination of the important sample characteristics noted above.

In regards to generalization of the results of this study, statistically one may say that the findings are generalizable to the populations from which the samples were drawn; however, generalizing the results obtained in a controlled laboratory setting to other settings must be done with caution. It is unclear under what conditions this deficit obtained in a controlled laboratory setting may impact daily functioning and in particular, impair learning and achievement within an educational context. While proceeding carefully from basic science to clinical practice is required, such findings can and do serve to inform clinical research as a foundation for clinical
intervention studies. Furthermore, in the era of clinician-scientist practitioner models, informed clinicians and educators working with ADHD children should have knowledge of this cognitive impairment and its potential impact on a child’s functioning.

Another possible limitation of the present studies, and an issue to be considered in future research, is that the ability to accurately self-detect errors may vary as a function of task parameters. The tasks used may not have allowed for appropriate self-detection of performance because of task demands for speed and accuracy. A future study employing the two flanker conditions used and a third “Self-Report” condition that asks participants to report on their self-detection of errors and correct responses, would determine if participants are able to self-detect their performance under the task parameters used in this research. Another limitation of the tasks used is that they may not have been optimal for determining if children with ADHD adjust differently than controls following correct responses. Future research should explore performance monitoring within a variety of tasks in order to fully comprehend how the process is impacted, if at all, by task/situational parameters.

The present research was limited by only having the Digit Span task of the WISC-IV to assess working memory. As theories suggest significant working memory involvement in performance monitoring processes, it would have been helpful to have had other measures of working memory to more fully assess any potential relationships between the two. In addition, future research would benefit from establishing associations between performance monitoring and a wide range of executive functions. This would help to determine if performance monitoring is highly predictive of other executive functions and to further evaluate where it lies in the hierarchy of other ADHD executive functions deficits.
Similar to the limited working memory measure used, the studies used only academic achievement measures as proxies of learning. Given that such measures often tap into crystalized knowledge (i.e., the ability to use already acquired skills, knowledge, and experience), and are not true learning tasks that likely use fluid reasoning skills (i.e., the capacity to solve novel problems independent of acquired knowledge), it would be beneficial for future research to examine adjustment within a true learning task.

Extending the investigation of adjustment following errors in ADHD to include tasks where different forms of adjustment, such as speeding up one’s reaction time, would be beneficial. Speeding after errors may occur on a task that requires slow responding to be accurate, with errors arising when responding is too slow. Through replication of the deficit using a post-error adjustment other than slowing, this would further specify the performance monitoring deficit evident in ADHD as one of error processing.

Future research into error processing in ADHD may include examining trial-by-trial data. This would allow for an understanding of inter-trial adjustment and if adjustment is related to unique sequences of trial-by-trial performance. Trial-by-trial data would also help examine any potential differences in feedback-related reinforcement. For example, determining if the amount of post-error adjustment is proportional to the probability of correct responding on the next trial would be one way to examine this. One could hypothesize that these are proportionally related in controls, but are not (or are differentially related) in ADHD. Such results would further support the findings of the present studies which found that feedback enhances performance in typically developing children, but not in children with ADHD.

The current research indicates reinforcement learning difficulties in children with ADHD, which converges with other studies. The impact of reinforcement and reward on error
processing ability in ADHD should be further investigated to inform possible interventions. More specifically, because the present research found that providing accurate performance feedback did not normalize the deficit found in children with ADHD or unaffected siblings, it would be of both research and clinical interest to determine if a behavioural manipulation of the adjustment phase of error processing can normalize the deficit. For example, a version of the flanker task where children are reinforced when they adjust appropriately would determine if the provision of reinforcement for appropriate adjustment has an effect on error processing, as reinforcement has been shown to improve several executive functioning deficits in ADHD. If children with ADHD slow following an error and are reinforced for this, then it would be assumed that they will be motivated to continue adjusting. However, if they still do not adjust as much as typically developing children, then such a result would suggest that their abnormal modulation of adjustment cannot be normalized with reinforcement. Careful consideration to reinforcement schedules and response-reinforcement delay should be given to such studies as research has demonstrated that children with ADHD prefer immediate versus delayed rewards (Sonuga-Barke, 2003), exhibit deterioration of performance under conditions of partial compared to continuous reward (Douglas & Parry, 1994), and have less effective reinforcement learning as the response-reinforcer delay is increased (Lattal & Gleeson, 1990; Grice, 1948).

The literature on cognitive processes in ADHD consistently reports improvement in task performance for this group while on stimulant medication (Pelham, Milich, & Walker, 1986; Berman, Douglas, & Barr, 1999). In addition, behavioural research on children with ADHD has shown that stimulant medication increased post-error adjustment on a Sternberg task, while also increasing speed and accuracy (Krusch, et al., 1996). Furthermore, ERP studies that investigated the effects of methylphenidate in children with ADHD found they made fewer errors in both low
and high-conflict conditions and that methylphenidate normalized Pe amplitudes (Groom et al., 2013) Jonkman et al., 2007; Groen et al., 2008). This suggests a link between dopamine function and error processing as the presumed mechanism of action of methylphenidate is the blocking of reuptake of dopamine into pre-synaptic neurons. Although this effect of methylphenidate is widespread, it has a particularly prominent effect in the striatum which modulates the ascending dopamine neurotransmission involved in error processing. Despite these promising results, the research into the effects of stimulant medication on error processing in ADHD is still very limited. Such research is extremely relevant to ADHD as stimulant medications are the most commonly prescribed treatment for individuals with the disorder.

Results from the present studies indicate that errorless learning appears to be a relative strength for children with ADHD compared to learning from errors. Clearly it is important for individuals to learn from both errors and success; however, task and situational demands as well as cognitive impairment may dictate which type of learning is best. For example, in the present tasks used, it appears that it was critical to detect and adjust to both errors and correct responses. Errorless learning has been found to be helpful for individuals with memory impairments when learning certain types of tasks (Clare & Jones, 2008). However, these benefits are not evident for all memory-impaired groups. The proposed mechanism of errorless learning’s effectiveness in this population is that, while individuals with adequate memory function can recall their mistakes and learn from them, individuals with memory impairment may have difficulty recalling errors and how to avoid (i.e., learning from them) and as a result, may default to erroneous responses over correct responses. As many studies have shown working memory impairments in ADHD and the present study suggested potentially adequate errorless learning in ADHD, it is possible that children with ADHD learn similarly to some memory-impaired
participants on particular tasks. Future research on ADHD can examine this further by drawing on a study that examined whether learning a task using “trial-and-error learning” versus “errorless learning” transferred a performance advantage to a similar but novel transfer task within a healthy young adult population (Jones, Clare, MacPartlin, & Murphy, 2010). Results indicated that during the novel transfer task, the trial-and-error group performed significantly better than the errorless group. These results suggest that trial-and-error learning may be better when there is a requirement to recall and transfer a skill learned during an acquisition task to a new, but skill-related task. Such a study using children with ADHD would have significant educational implications by elucidating if ADHD participants can recall and apply a transferable skill better if learned from errorless versus trial-and-error learning.

In terms of considering the findings of familiality of error processing and its use as a candidate endophenotype of ADHD, several limitations and considerations for future research are also evident. In particular, there are limitations to the genetic research utility of error processing as an endophenotype. While error processing is normally present, there is most likely task-by-task variation, as was shown in the present study with regards to the No Feedback and Feedback conditions. Error processing outcomes may vary due to the use of different cognitive tasks and levels of difficulty, characteristics of the individual including medication status, and task performance variables such as error rates (Manoach, 2013). Such methodological differences across research studies may lead to divergent or conflicting findings. Currently, due to measurement variability and an absence of large-scale studies, it is difficult to define clear cut-offs for “normality” (Manoach, 2013). As such, a standardized procedure yielding “norms” for assessing error processing will need to be adopted by researchers if it is to be used as an endophenotype of ADHD.
Another important area for future research will be to determine if the familiality of the error processing deficit in ADHD persists into adolescence and adulthood. For example, one study did not find a post-error adjustment deficit in adolescents with ADHD and their unaffected siblings while performing a modified flanker task, causing the authors to argue that deficient error processing may be a feature of childhood ADHD, but not a “cardinal feature” of adolescents with ADHD (Wild-Wall, Oades, Schmidt-Wessels, Christiansen, & Falkenstein, 2009). However, it is clear from the present research that statistically significant error processing deficits appear only under some circumstances and not others. Also, it is possible that flanker tasks, as was used in Wild-Wall et al. (2009), reach a ceiling as one ages and therefore may not be the best task to use when examining error processing in older age samples. As developmental differences in potential endophenotypes of ADHD have been found, further study of error processing in ADHD throughout the lifespan is warranted in order to determine if its use as a potential endophenotype is limited to childhood.

The present research employed a sibling methodology to assess familiality of error processing. Future research should consider other approaches to assess error processing as an endophenotype of ADHD. In particular, a twin study that examines genetic and environmental contributions to error processing and ADHD, as well as the co-heritability of the two, would be useful. Longitudinal or retrospective research may also be able to establish temporal relationships of error processing and ADHD by examining whether error processing deficits at time 1 increase risk for ADHD at time 2. Establishing such temporal relationships may be beneficial to exploring causal links. It may be that a child displays error processing deficits first and later develops ADHD, which may indicate some causal factors that are specifically related to
error processing and that contribute to the development of psychopathology later in life (Ma et al., 2015).

As the current research found deficits in post-error adjustment in unaffected siblings of children with ADHD, it highlights the importance of research within the ADHD sibling population. Focusing on this population may contribute to our understanding of how similar genetic and shared environmental factors lead to different outcomes. “That is, what factors determine whether or not a child develops ADHD despite similar genetic backgrounds and similar family environments?” (Ma et al., 2015). In addition, sibling studies are needed to inform prevention and treatment programs given the high risk of psychopathology and even sub-threshold, or sub-cut-off, psychopathology in siblings, and the corresponding impact this has on families and other broader systems such as schools, health care systems, and communities. Such studies could facilitate increased clinician and parental awareness of the elevated risks to siblings and may allow for early intervention, support structures, and treatment modalities that are inclusive of siblings, affected or unaffected (Ma et al., 2015).

In summary, the results of the current research specified an error processing deficit in children with ADHD. This deficit was not significantly improved by the provision of performance feedback. Furthermore, it was found that children with ADHD are not as strategic in their adjustment modulation following both errors and correct responses compared to typically developing children. This research also found atypical error processing in unaffected siblings of children with ADHD, indicating familiality of this deficit. Overall, these findings elucidate of the specific nature of the deficit in children with ADHD and advance future research and interventions targeting performance monitoring in ADHD.
References


Wild-Wall, N., Oades, R. D., Schmidt-Wessels, M., Christiansen, H., & Falkenstein, M. (2009). Neural activity associated with executive functions in adolescents with attention-


Appendix A. DSM-IV-TR criteria for Attention Deficit Hyperactivity Disorder

A. Either (1) or (2):

(1) six (or more) of the following symptoms of inattention have persisted for at least 6 months to a degree that is maladaptive and inconsistent with developmental level:

Inattention
- a) often fails to give close attention to details or makes careless mistakes in schoolwork, work, or other activities
- b) often has difficulty sustaining attention in tasks or play activities
- c) often does not seem to listen when spoken to directly
- d) often does not follow through on instructions and fails to finish schoolwork, chores, or duties in the workplace (not due to oppositional behavior or failure to understand instructions)
- e) often has difficulty organizing tasks and activities
- f) often avoids, dislikes, or is reluctant to engage in tasks that require sustained mental effort (such as schoolwork or homework)
- g) often loses things necessary for tasks or activities (e.g., toys, school assignments, pencils, books, or tools)
- h) is often easily distracted by extraneous stimuli
- i) is often forgetful in daily activities

(2) six (or more) of the following symptoms of hyperactivity-impulsivity have persisted for at least 6 months to a degree that is maladaptive and inconsistent with developmental level:

Hyperactivity
- a) often fidgets with hands or feet or squirms in seat
- b) often leaves seat in classroom or in other situations in which remaining seated is expected
- c) often runs about or climbs excessively in situations in which it is inappropriate (in adolescents or adults, may be limited to subjective feelings of restlessness)
- d) often has difficulty playing or engaging in leisure activities quietly
- e) is often “on the go” or often acts as if “driven by a motor”
- f) often talks excessively

Impulsivity
- g) often blurts out answers before questions have been completed
- h) often has difficulty awaiting turn
- i) often interrupts or intrudes on others (e.g., butts into conversations or games)

B. Some hyperactive-impulsive or inattentive symptoms that caused impairment were present before age 7 years.

C. Some impairment from the symptoms is present in two or more settings (e.g., at school [or work] and at home).
D. There must be clear evidence of clinically significant impairment in social, academic, or occupational functioning.

E. The symptoms do not occur exclusively during the course of a Pervasive Developmental Disorder, Schizophrenia, or other Psychotic Disorder and are not better accounted for by another mental disorder (e.g., Mood Disorder, Anxiety Disorder, Dissociative Disorder, or a Personality Disorder).

*Code* based on type:

**314.01 Attention Deficit/Hyperactivity Disorder, Combined Type:**
if both Criteria A1 and A2 are met for the past 6 months

**314.00 Attention Deficit/Hyperactivity Disorder, Predominantly Inattentive Type:**
if Criterion A1 is met but Criterion A2 is not met for the past 6 months

**314.01 Attention Deficit/Hyperactivity Disorder, Predominantly Hyperactive Impulsive Type:**
if Criterion A2 is met but Criterion A1 is not met for the past 6 months

*Coding note:* For individuals (especially adolescents and adults) who currently have symptoms that no longer meet full criteria, "In Partial Remission" should be specified.