ASSESSMENT OF ERROR PROCESSING AND CATEGORY LEARNING IN CHILDREN WITH ADHD

A Thesis in
Psychology
by
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Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

May 2012
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Previous studies have suggested that children with Attention Deficit Hyperactivity Disorder (ADHD) show greater difficulty processing error feedback information as compared to their same-aged peers. The ability to use the information provided in feedback is often behaviorally operationalized by the degree to which individuals slow down after committing an error, a phenomenon known as post-error slowing. This study evaluated post-error slowing in a category-learning paradigm from a developmental perspective. It further assess for between group differences in post-error slowing in children with and without attentional difficulties. Results indicated that typically developing children are less able to use feedback information to inform future behavior as compared to adults. Furthermore, children with elevated levels of inattention/hyperactivity showed an inverse relationship between post-error slowdown and accuracy. These findings suggest a potential endophenotype regarding the source of learning difficulties in children with ADHD.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
<td>v</td>
</tr>
<tr>
<td>List of Figures</td>
<td>vi</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>The Study of Skill Acquisition</td>
<td>5</td>
</tr>
<tr>
<td>Error Feedback and Category Learning</td>
<td>12</td>
</tr>
<tr>
<td>Skill Acquisition and Error Feedback Processing in ADHD</td>
<td>18</td>
</tr>
<tr>
<td>Summary and Current Study</td>
<td>24</td>
</tr>
<tr>
<td>Methods</td>
<td>25</td>
</tr>
<tr>
<td>Participants</td>
<td>25</td>
</tr>
<tr>
<td>Diagnostic Questionnaires</td>
<td>27</td>
</tr>
<tr>
<td>Procedures</td>
<td>29</td>
</tr>
<tr>
<td>Performance Measures</td>
<td>31</td>
</tr>
<tr>
<td>Statistical Analyses</td>
<td>34</td>
</tr>
<tr>
<td>Results</td>
<td>36</td>
</tr>
<tr>
<td>Discussion</td>
<td>57</td>
</tr>
<tr>
<td>Skill Acquisition in a Categorization Learning Paradigm</td>
<td>58</td>
</tr>
<tr>
<td>Measures of Post-error Slowing</td>
<td>60</td>
</tr>
<tr>
<td>Post-error Slowing in a Learning Paradigm</td>
<td>66</td>
</tr>
<tr>
<td>Post-error Slowing in ADHD</td>
<td>68</td>
</tr>
<tr>
<td>Theories of Post-error Slowing</td>
<td>71</td>
</tr>
<tr>
<td>Summary</td>
<td>74</td>
</tr>
<tr>
<td>Bibliography</td>
<td>75</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1. ADHD symptoms. 37
Table 2. Demographic data. 38
Table 3. Percent Accuracy and correct reaction time (CRT) across block. 40
Table 4. Learning Curve slope analyses. 42
Table 5. Analysis of Group and Block effects. 43
Table 6. Post-error slowing across block as measured by the raw RT value for the first correct response after an error (PERT), the absolute difference in PERT and CRT, the proportional relationship between PERT to CRT, and the z-score of PERT in relation to an individuals’ observed CRT variability. 47
Table 7. Relationship between PES and accuracy/sorting strategy. 49
Table 8. Predictive ability of PES to accuracy & sorting strategy by block. 50
Table 9. Sorting strategy predicting accuracy by block. 55
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Stimulus plot</td>
<td>30</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Category learning paradigm</td>
<td>32</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Accuracy &amp; Correct Reaction Time across block</td>
<td>41</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Post-error Slowing across block</td>
<td>45</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Relationship between block 1 PES and block 1 accuracy.</td>
<td>51</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Relationships between block 1 PES and block 1 sorting strategy</td>
<td>56</td>
</tr>
</tbody>
</table>
Introduction

Attention deficit hyperactivity disorder (ADHD) is a highly prevalent childhood disorder occurring in approximately 8.4% of school-aged children (2008). Although individuals with ADHD display a heterogeneous constellation of maladaptive behaviors, consistent across many findings are strong associations between ADHD and (1) academic underachievement (Barkley, 1997; Frick, et al., 1991; Hinshaw, 1992), and (2) problems with peer relationships (Bagwell, Molina, Pelham, & Hoza, 2001; Friedman, et al., 2003; Greene, Biederman, Faraone, Sienna, & Garcia-Jetton, 1997). Many children with ADHD also exhibit comorbidities with other mental health disorders, the most frequent of which are learning disabilities and externalizing behavior problems such as Oppositional Defiant Disorder and Conduct Disorder (Ollendick, Jarrett, Grills-Taquechel, Hovey, & Wolff, 2008). These increased physical, emotional, and academic risks result in a higher likelihood for children with ADHD to use educational supports and to enlist in health care services (Statistics, 2008). Conservative estimates of the societal costs and economic impact of ADHD – as assessed by expenses incurred in health care, education and crime – ranges from $36 to $52.4 billion annually (Pelham, Foster, & Robb, 2007), highlighting the grave economic and societal import of continued research in this field of study. Further efforts in the development of effective evidence-based educational and social-relational therapies in ADHD would serve to alleviate some of these costs on behalf of 4.5 million school age children in the United States.

As identified by the DSM-IV-TR, ADHD is a behavioral syndrome marked by severe age-inappropriate levels of sustained attention, impulse control, and activity level modulation (Diagnostic and Statistical Manual of Mental Disorders (4th ed., text
These symptoms must begin at an early age and be present in multiple environments (e.g., home and school). Theoretical approaches to the etiology of ADHD can generally be broken down into two camps: (1) deficits extending from either top-down, higher order control executive control processes (Barkley, 1997) (Pennington & Ozonoff, 1996; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), and (2) bottom-up, motivation and drive related processes such as an altered reward system (Sonuga-Barke, 2002), and arousal level/state factors (Sergeant, 2000). Many research studies examining the relationship between these aforementioned constructs and ADHD have generally shown moderate levels of association (Nigg, 2005; Willcutt, et al., 2005).

Both higher order executive systems and motivational/activational systems contribute to the appropriate modulation of behavior and affect. Such systems interact through an error monitoring system in the brain, which connects the reward and expectancy circuits to motor control areas and regions responsible for higher cognitive functions (e.g., planning and set shifting) (Gehring, Goss, Coles, Meyer, & Donchin, 1993). The theoretical role of the error monitoring system is to call up additional attentional and other higher order cognitive resources when a response does not meet an expected degree of success (Ohlsson, 1996).

A number of common behavioral characteristics frequently seen in children with ADHD – including poor decision making (Luman, Oosterlaan, Knol, & Sergeant, 2008), decreased responsiveness to future consequences (Aase & Sagvolden, 2006), and an inability to modify behavior to environmental demands (Aase & Sagvolden, 2005) – suggest that a breakdown in the error monitoring system may be an important component to understanding the disorder (Albrecht, et al., 2008; Barkley, 1997). Further organic
evidence of an error monitoring deficit in ADHD has also been found in functional (Depue, et al., 2010; Durston, et al., 2007), structural (Castellanos, et al., 2002; Seidman, Valera, & Makris, 2005), and neural connectivity studies (Konrad & Eickhoff, 2010).

Much of the current research investigating error monitoring in ADHD has primarily used speeded reaction time tasks tapping specific inhibitory processes (e.g., stop signal reaction time (Liotti, Pliszka, Higgins, Perez, & Semrud-Clikeman, 2010; Schachar, et al., 2004), flanker (Herrmann, et al., 2009; Jonkman, van Melis, Kemner, & Markus, 2007; Van Meel, Heslenfeld, Oosterlaan, & Sergeant, 2007) and Go/NoGo (Wiersema, van der Meere, & Roeyers, 2005)) tasks. These studies have found equivocal results, with some reporting a deficit in error monitoring in children with ADHD and others reporting no significant group differences in comparison to non-ADHD controls. Although post-error behavior modification on these measures reflect generalized reactivity to having committed an error, the simplicity and relative automaticity of such paradigms do not tell us anything about how feedback is being used to improve future performance. What do children with ADHD do with the information provided by feedback; do they use this information advantageously to learn and acquire new skills? The inability for an individual to effectively utilize feedback may negatively impact their ability to acquire new skills as they would be less able to learn from their mistakes. Such a deficit could help explain the high rates of academic underachievement seen in children with ADHD.

To gain further insight on the phenomenon of error processing and whether it predicts the degree to which children with ADHD are able to learn new skills, the current study will examine the association between post-error behavior and accuracy in a trial-
and-error type categorization-learning task. Only a handful of studies have explicitly examined the potential factors that contribute to how children with ADHD acquire new skills and information, and even fewer have looked at the association between error monitoring and its effects on future performance in this group. If error-feedback monitoring is important to skill acquisition in children, then a positive correlation between error-feedback reactivity and accuracy would be predicted. As previous studies have suggested that error processing skills improves over development (Crone, Jennings, & van der Molen, 2004; Hämmerer, Li, Müller, & Lindenberger, 2010), it is expected that non-ADHD children will show a weaker relationship between skill acquisition and post-error behavior modification as compared to adults. However, dependence upon accuracy alone is only the first step to quantifying performance because participants may achieve identical accuracy rates via separate performance strategies. Thus, it is also predicted that in adults, a stronger response to errors will be associated with the adoption of the correct response strategy such that the relationship between behavioral change exhibited in post error-feedback and accuracy is mediated by the adoption of the correct response strategy. Likewise, as compared to typically developing controls, children with ADHD would be expected to show less behavioral modification after error-feedback, hindering the adoption of the correct response strategy, thereby prohibiting accurate performance. In summary, the intent of my current research is to examine whether or not a deficit in post-error behavioral modification exists in children with ADHD on a task designed to measure skill acquisition in the form of category learning.
The Study of Skill Acquisition

Skill acquisition, as defined as the development of increasingly proficient performance on a task as a result of repeated experience with that task, allows people to continuously adapt to a highly variable world. Historically, cognitive theories regarding the acquisition of knowledge and skill have focused on problem solving procedures in adults (e.g., trial-and-error, hill climbing, means-ends analysis) (Anderson, 1982; Logan, 1988). The most prominent theories generally depict a multistep process that emphasizes an initial slow, declarative component to goal-oriented behavior (Anderson, 1982, 1987). Increased proficiency and automaticity is achieved through encoding an initial approximation of the desired behavior, a gradual refining of the behavior, and finally compiling the multiple cognitive procedures involved in the skill into a single procedure (Anderson, 1987; Fitts, 1964; Logan, 1988). Hallmark characteristics of these models include heavy reliance on executive functioning, particularly WM capacities, in the development of automaticity (Anderson, 1982; Logan, 1988).

One of the many ways by which people acquire new information and skills is by taking measure of the benefits and/or consequences of their behavior, be it purposefully or below conscious levels of detection. This is especially relevant in the world of a child, where there are a lot of unknowns, ever moving targets of success, and shifting environmental demands. Such phenomena calls to bear Thorndike’s law of effect, first laid forth in 1911. Thorndike described how actions that are followed by feelings of satisfaction are more likely to be repeated than those that have negative outcomes (Thorndike, 1927). This underlying principle of reinforcement learning highlights a role for feedback processing in skill acquisition. Although the development of cognitive
procedures of thought/action can happen with or without instructive feedback, studies have consistently found that the provision of feedback has profound impacts on the ability to procure knowledge and learn new skills (Metcalfe & Kornell, 2007). The characteristics that optimize feedback efficacy (e.g., timing of when it is provided, valence, etc.) vary depending on the specific characteristics of the learning paradigm (e.g., task difficulty) (Metcalfe, Kornell, & Finn, 2009; Schmidt & Bjork, 1992). Even when taking the differences by which feedback is incorporated into an individual’s learning schema into consideration, all evidence points to the functional utility of feedback in learning and skill acquisition.

Error feedback processing is a proposed cognitive mechanism by which incoming information regarding an incorrect response is used to enhance performance (Ohlsson, 1996). Ohlsson’s dissociation hypothesis of feedback processing breaks this monitoring system down into two distinct mechanisms: action selection and action evaluation. The selection mechanism initiates, organizes, and executes an action. The evaluative component is thought to be a declarative mechanism that assesses outcome information and allows the learner to judge the consequences of his/her actions. These judgments can be compared to a number of sources, including previous task specific knowledge or generalized action schemas that match some aspect of the task. Discrepancies and conflicts between intended and perceived results during these mental comparison exercises indicate the presence of an error.

During skill acquisition, errors occur when there is more than one option in action selection, a limited number of which achieves the goal state. Ohlsson (1996) suggests that, due to the overly-general activation of multiple plausible procedures by which one
may attain his/her goal are activated during these first time encounters (and, for that matter, during familiar encounters as well), an evaluation of the environmental circumstances is necessary to deduce which internal rule governing action and behavior ought to be selected and executed. Action selection during unfamiliar tasks involves sifting through the entire range of possible goal-oriented procedures within the constraints of the situational demands. Probability rules predict that it is therefore possible (and, in the beginning, highly likely) that the wrong action path will be selected, resulting in an error. Therefore, it is not enough for learners to acquire knowledge of the currently operating behavioral rule, but it is also necessary to decrease the strength of the other action patterns that may have been activated due to stimulus onset alone (Ohlsson, 1996). In other words, error correction involves updating the underlying cognitive representations on the basis of these mismatches, as well as inhibiting the activation of other competing action procedures. Skill learning, then, is the specialization of the rules that initiate action through the incorporation of additional information about the task into the current condition. This process, too, is error prone, in that it requires the correct identification of the rule that needs to be specified, as well as figuring out the aspect of that particular rule that is wrong. Hypothesis testing – the verbal, declarative process in which people try to explain to themselves why something did not turn out as expected – is one possibility for how errors are corrected when explicit feedback regarding the source of the error is not provided (Ohlsson, 1996).

Studies conducted in the late 1990s reshaped the role positive feedback and reward presumably had on the neural mechanisms of learned behavior (Holroyd & Coles, 2002; Schultz, 1998). During novel events, phasic bursts of mesencephalic DA activity
appear upon reward presentation (Schultz, 1998). As learning takes place, these DA signals propagate back in time towards the presentation of the stimulus itself; eventually, the conditioned response is able to elicit DA phasic firing, transforming the original reward signal into an anticipatory signal (Richardson & Gratton, 1996; Schultz, Apicella, & Ljungberg, 1993). Burst activity decreases for omissions in expected outcomes (negative-prediction errors) (Schultz, et al., 1993), and when conditioned stimuli predict punishment (Guarraci & Kapp, 1999; Mirenowicz & Schultz, 1996). One hypothesized role for this pattern of signal propagation is that modifications in burst timing of dopaminergic neurons serves as a predictive indicator for when results do not meet expected outcomes (Holroyd & Coles, 2002). Schultz et al. (1994) proposed that the changing activity levels of these DA neurons serves to adjust the strength between stimuli and response during feedback learning processes. Evidence at the cellular level implicate a potential mechanism for how feedback processing moderates long-term potentiation and long-term depression via basal ganglia DA modulation of corticostriatal interactions (Calabresi, Pisani, Mercuri, & Bernardi, 1996; Wickens, Begg, & Arbuthnott, 1996). When such phenomenon occurs, the resultant interdomain communication would allow for the modification of behavior during task acquisition by potentially initiating motor reactions, recruiting greater attentional resources, and implementing higher order executive functions (Devinsky, Morrell, & Vogt, 1995).

From a developmental perspective, the influence of error processing on skill acquisition and learning has been found to increase incrementally with age (Eppinger, Mock, & Kray, 2009; Hämmerer, et al., 2010). The ability to effectively utilize feedback to maximize action-outcome relations is represented by an inverted U-shaped
developmental trajectory that peaks in young adulthood (Hämmerer, et al., 2010). Cross-sectional studies evaluating behavioral and psychophysiological measures of performance monitoring in children, adolescents, and adults have shown that the use of feedback to improve performance increases in efficacy with age across a number of tasks including spatial rule-switching tasks (Crone, Ridderinkhof, Worm, Somsen, & van der Molen, 2004; Crone, Somsen, Zanolie, & van der Molen, 2006), cued sorting tasks (Van Duijvenvoorde, Zanolie, Rombouts, Raijmakers, & Crone, 2008), and probabilistic reinforcement learning tasks (Crone, Jennings, et al., 2004; Hämmerer, et al., 2010). Brain regions associated with feedback learning in adulthood show relatively protracted periods of development (Sowell, 2004; Sowell, et al., 2003). Evaluation of potential dysfunction within this process could greatly inform whether or not there exists a deficit in skill acquisition in students with ADHD who struggle with academics and social interactions.

**Measures of error processing.** An increase in latency to the response following the commission of an error is regularly observed in simple choice reaction time tasks (Rabbitt, 1966). This increase in reaction time following an error, known as post-error slowing, is the most frequently employed behavioral proxy by which researchers index active error processing. The degree to which this form of performance related behavioral adjustment manifests itself has traditionally been quantified by subtracting the average correct reaction time after a correct response from the average correct reaction time after an error has been committed (Rabbitt, 1966, 1968). This delay in response has been presumed to reflect some as yet undetermined compensatory mechanism meant to
increase the likelihood of executing a correct response, although its theoretical underpinnings are currently under debate.

Neurophysiological studies of post-error slowing using stop-signal reaction time and go/no-go tasks have linked increased BOLD signals in the dorsal ACC, and ventro- and dorso-lateral prefrontal cortices to post-error behavioral changes in performance (Li, Huang, et al., 2008; Li, Yan, et al., 2008). These regions have previously been identified as part of the error processing and conflict monitoring neurocircuitry. Specific to error monitoring, some data suggests the notion that post-error slowing is functionally related to improvements in performance as reported in action monitoring studies using the Stroop task (Hajcak, Mcdonald, & Simons, 2003), high conflict tasks (Marco-Pallarés, Camara, Münte, & Rodriguez-Fornells, 2008), a modified Simon task (Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011), and a simple reaction time task (Rabbitt, 1966). In a study involving the learning of word pairs, one study found that providing individuals with corrective feedback along with an appropriate amount of time to process the information during training resulted in larger increases in word retention 1 week later as compared to experimental conditions that did not provide the extra time (Pashler, Cepeda, Wixted, & Rohrer, 2005). The ability to use post-error slowing to influence the acquisition of skilled behavior is present in school-aged children performing the Flanker task (Davies, Segalowitz, & Gavin, 2004), and continues to develop over time. It appears that the extent to which the behavior reflects an ability to effectively engage in error processing parallels the development of executive control abilities (Davies, et al., 2004; Hämmerer, et al., 2010).
Several cognitive theories exist regarding the origins of post-error slowing. Error detection theorists view the phenomenon as a volitional response; intentional behavioral inhibition to prevent committing another error or for the purpose of reflecting on the mistake (Rabbitt, 1966). Although there is some data to suggest an association between error awareness and post-error slowing magnitude (Jentzsch & Leuthold, 2006; Rabbitt, 1966), it is difficult to behaviorally operationalize intentionality to falsify such a hypothesis. Reinforcement learning theories, on the other hand, hypothesize that post-error slowing derives from the continuous monitoring of valence values comparing an executed response to reward expectations. Unforeseen unfavorable outcomes consequently influence effortful attentional control from perception to control mechanisms (Holroyd, Yeung, Coles, & Cohen, 2005). The view of post-error slowing from conflict control theorists, is one reflective of the behavioral manifestation of reduced response activation resulting from the initiation of control mechanisms triggered by the presence of consecutive, parallel, discrepant streams of information (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Carter & van Veen, 2007). Evidence from computational modeling (Botvinick, et al., 2001) and neurophysiological studies (Di Pellegrino, Ciaramelli, & Làdavas, 2007) have provided some support for this theory of post-error slowing. In contrast, Notebaert and colleagues support an orienting account that denies the presence of cognitive control and instead identifies post-error slowing as an automatic response to a rare event (Notebaert, et al., 2009). Still in its early stages of development, the orienting hypothesis describes post-error slowing as a reflexive, attentional response to rare events that interferes with the subjects ability to perform the task at hand resulting and results in response inhibition (King, Korb, von Cramon, &
Continuing research efforts are aimed towards working to distinguish between these theoretical frameworks for post-error slowing (Bissett & Logan, 2011; Jentzsch & Dudschig, 2009; King, et al., 2010). Orienting theorists aside, most researchers, regardless of theoretical orientation, infer that post-error slowing demonstrates the activation of some level of attentional or higher level processing in the service of achieving a particular goal, whether it be to reduce conflict or in learning (Botvinick, et al., 2001; Holroyd & Coles, 2002; Rabbitt, 1966). Given the extensive amount of evidence around this variable and its relationship with the psychophysiology of error monitoring, and neurophysiological evidence of executive cortical functioning during post-error adjustment periods, post-error slowing serves as the most apropos behavioral proxy available in the study of cognitive processing in performance monitoring.

**Error Feedback and Category Learning**

In order to form a more complete portrait of how children improve in task mastery over time, studies must necessarily apply current understandings of developmental changes in mental capacities to cognitive models of skill acquisition. Imaging studies of the structural development of the brain shows protracted periods of development in the prefrontal cortex, responsible for much of the higher order cognitive processes in the brain (Giedd, et al., 1999; Gogtay, et al., 2004). Such changes in the brain have been associated with the continued growth of attention, memory, and executive functioning abilities from childhood through adolescence (Casey, Tottenham, Liston, & Durston, 2005). Based on the advances in the study of neurophysiology, how these changes
influence what we know about cognitive models of skill acquisition has become a
burgeoning field of research. Models of skill acquisition have greatly expanded in recent
years to include functional (e.g., rule-based models, signal detection models, selective
attention models), computational (e.g., COVIS, ALCOVE, ITAM) (see Palmeri, Wong,
& Gauthier, 2004 for review), neuronal (e.g., Hebbian model, Rescorla-Wagner model),
and molecular (e.g., dopamine model) level models. These finer grained models help us
better understand how skilled task execution is achieved by isolating the specific
mechanisms through which the processes are carried out. Likewise, they additionally
provide opportunities to examine how failures in skill acquisition may occur. In
particular, distilled descriptions of these potential skill acquisition processes and
mechanisms provide a backdrop by which to study children who struggle in academia.
Similarly, the final critical element to this type of examination is the inclusion of a
paradigm that: (1) has a strong theoretical and evidentiary base in the cognitive literature,
(2) has been validated across developmental periods, and (3) has been examined from a
developmental framework. Perceptual categorization learning qualifies as such a
paradigm by which to study the development of cognitive skill acquisition in children.

A paradigm of skill acquisition: category learning. The means by which people
coaalesce environmental stimuli into their memory and skill set are numerous and, to a
large degree, remain somewhat of a mystery. However, one basic cognitive skill that is
critical and common throughout many models of information acquisition is the ability to
organize objects into categories.

Categorization processes serve to reduce information load, assist in language
acquisition, and influence the formulation of inferences, predictions, and decisions that
subsequently affects human behavior (Grossmann, Gliga, Johnson, & Mareschal, 2009; Madole & Oakes, 1999). Category learning is a model phenomenon to study potential deficits in skill acquisition and learning for a number of reasons. The ability to accurately categorize environmental elements into simple groupings – ‘safe/dangerous,’ ‘same/different,’ or ‘friend/foe’ – has been perpetuated throughout evolutionary history (Cook & Smith, 2006; Kepecs, Uchida, Zariwala, & Mainen, 2008; Smith, Chapman, & Redford, 2010), and emerges early on in human development (French, Mareschal, Mermillod, & Quinn, 2004; Mandler, 1992; Pauen & Träuble, 2009), emphasizing its relevance to survival and fitness. Additionally, categorization occurs on a frequent basis in everyday life, so much so that the process is often automatic and effortless, proceeding with little awareness. The manifold use of this skill speaks to its wide applicability across an array of settings. Finally, extensive research from the cognitive sciences on theoretical models of category learning (Ashby & Maddox, 2005; Keri, 2003) provides a strong foundation from which to generate hypotheses.

**The development of category learning.** Much research has already been conducted on the developmental course of category learning (Hammer, Diesendruck, Weinshall, & Hochstein, 2009; Hayes, Foster, & Gadd, 2003; Kloos & Sloutsky, 2008). Behavioral and neurophysiological evidence for the presence of subordinate-level category representations are present in infants as young as 6 months of age (Quinn, Doran, Reiss, & Hoffman, 2010). Neural activity and behavioral assessment of observed changes in category learning abilities over time have been attributed to the gradual growth and development of key brain regions (Casey, Giedd, & Thomas, 2000; Casey, et al., 2005; Minda, Desroches, & Church, 2008). Specifically, maturation of the prefrontal
cortex and caudate nucleus are believed to be important for buttressing category-learning abilities by increasing EF skills and WM capacity (Minda, et al., 2008).

**COVIS model of category learning.** Within the broad spectrum of category learning types is a phenomenon known as perceptual categorization – the ability to sort and categorize objects based on the stimuli’s physical attributes (Ashby & Maddox, 2005). Much research in the field of cognitive psychology has evaluated perceptual categorization abilities. Among the currently existing viewpoints on this subject is a multiple systems theory that suggests the presence of at least two distinctive systems of category learning: an explicit, verbal system and an information-integration, procedural learning system (Ashby, Alfonso-Reese, Turken, & Waldron, 1998). This model, known as COVIS (competition between verbal and implicit systems), operates under the assumption that humans possess an array of categorization tools by which they learn to differentiate relevant features of variable environment (Smith, et al., 2010). Explicit category learning, which is thought to be dependent on the cingulate and prefrontal cortices, operates via a hypothesis testing procedure where an easily verbalized theory is continuously tested and updated until an optimal rule is attained (Ashby, et al., 1998). Examples of easily verbalized rules include single feature (if…then), conjunctive (if…and if…then), disjunctive (if…or if…then), and exceptions (if…then…except) (Minda, et al., 2008). Verbal skills, WM, and attentional control facilities play important roles in the successful performance of such rule-based tasks (Maddox, Ashby, & Bohil, 2003). Information-integration categorization tasks, mediated by the thalamus and striatum, require the assessment of multiple aspects of a stimulus along certain parameters in order to attain maximal accuracy and whose optimal “rule” is verbally...
difficult to express (Ashby, et al., 1998). Unlike rule-based categorization, where observations of distinct and separable stimulus parameters are made individually, here raw perceptual information gathered from multiple stimulus elements are integrated into the observation itself (Ashby & Maddox, 2005). Computing weighted linear combinations or treating stimuli as a gestalt are examples of information-integration type categorization paradigms (Ashby, et al., 1998). Determining whether or not you have time to pass a slow moving car in front of you or diagnosing pathology in a tissue biopsy are both information-integration type perceptual categorization decisions.

Neuropsychological predictions based on the COVIS model have been validated by a number of studies conducted in neuropsychiatric populations, including patients with Parkinson’s Disease (Ashby, Noble, Filoteo, Waldron, & Ell, 2003; Knowlton, Mangels, & Squire, 1996), Huntington’s Disease (Filoteo, Maddox, & Davis, 2001), and amnesics (Kitchener & Squire, 2000). Connectionist in nature, COVIS’s strengths lie in its capacity to explain behavior on multiple planes of analysis, including at the computational level. Principle among these is the ability to conduct model-based assessment of response patterns and the ability to examine the cognitive strategies by which subjects make decisions. Paradigms created from algorithmically pre-determined classification rules of varying degrees of verbalizeability generated along any number of dimensions allows for a wide array of experimental designs by which different types of perceptual categorization skill can be studied. The fitting of response patterns onto these dimensional models begets opportunities to evaluate qualitative differences in the development of proficiency over time in a manner that is more discriminative than measures of accuracy alone would permit. On the basis of these aforementioned reasons,
the COVIS model of category learning was selected as an apt cognitive paradigm by which to study skill acquisition in childhood ADHD.

Theories abound regarding the architecture of human categorization skills and the means in which we acquire the internal structures within the system. An important part of category learning is the ability to identify the similarity between objects within a category and recognize the attributes that are different from other categories in a hierarchical structure (Hammer, et al., 2009). Perceptual categorization is the ability to sort and categorize objects based on the stimuli’s physical attributes (Ashby & Maddox, 2005). There are several major models of category knowledge structures that differ from each other in terms of mental representation. In exemplar models of classification, memories of individual category members are retained in memory. Classification follows via comparison to each exemplar in memory storage. In prototype models, a prototype formed by averaging across all exemplars or through an amalgamation of probabilistic elements across exemplars serves as the basis for classification. Rule-based models conceptualize categories through matching certain rules or theories that circumscribe category inclusiveness. Finally, signal detection models surmises that objects are represented as occupying a probabilistic area (as a result of noise) within a three dimensional cognitive space. Decision bounds separating the space into regions are the basis of category determination (see Palmeri, et al., 2004 for review).

The role of feedback in acquiring category structures has also been previously evaluated in the COVIS model, with the discovery that although a delay in the provision of feedback does not affect rule-based category learning (Maddox, et al., 2003), the amount of time allowed for the processing of feedback information is crucial to the
acquisition of the correct category structures (Maddox, Ashby, Ing, & Pickering, 2004). However, learning from errors might be difficult for children due to the fact that they have a penchant for over-generalization and poorly developed verbal discriminatory abilities (Minda, et al., 2008). Researchers have found that, much like adult novices, children show over-generalized category representations during perceptual categorization (Mareschal, Quinn, & French, 2002). The ability to hypothesis test is also relatively weak in young children due to the protracted development of working memory ability and a bias towards categorizing objects based off of detected commonalities rather than through the identification of differences, limiting the scope of easily verbalizeable rules (Gentner & Namy, 1999; Hammer, et al., 2009). By adolescence, individuals are better able to identify and categorize objects based off of between group differences as verbal ability, working memory, and inhibitory control continue to develop over time (Hammer, et al., 2009).

**Skill Acquisition and Error Feedback Processing in ADHD**

Learning difficulties have long been associated with a diagnosis of ADHD. Of school-age children who have been diagnosed with ADHD, approximately 28% also qualify for learning disabilities (Statistics, 2008), upwards of 49% have been retained a grade (compared to 9% in controls) (Barkley, Anastopoulos, Guevremont, & Fletcher, 1991), and 32% drop out of the educational system before completing high school (Barkley, Fischer, Smallish, & Fletcher, 2006). Such academic struggles suggest a highly prevalent deficit in information acquisition and/or subsequent knowledge based performance in children with ADHD. Given the significant number of children with
ADHD who experience difficulties in school, identification and analysis of potentially the dysfunctional mechanisms underlying such difficulties with skill acquisition would have a powerfully positive impact on the development of efficacious scholastic remediation techniques. Since the pathway begins with information gathering, the means by which knowledge and skills are procured is a logical place to begin the investigation of potentially problematic learning processes in children with ADHD.

Unfortunately, the literature regarding whether or not the development of skill acquisition is difficult for children with ADHD is sparse. An early study examining the development of automaticity showed that, while the rate of improvement with practice was similar between school-aged children with ADHD vs. without ADHD in a task manipulating cognitive load, achieved accuracy and reaction time values in the ADHD group consistently remained behind those of unaffected children (Van der Meere & Sergeant, 1988). Huang-Pollock & Karalunas (2010) reported that the development of skilled performance varies depending on the working memory (WM) load demands of the to-be-learned task, where higher but not lower WM demands resulted in progressively greater difficulties in performance.

WM and other executive function (EF) weaknesses have long been implicated as explanatory factors in studies of academic problems in ADHD (Banich, 2009; Pavuluri, West, Hill, Jindal, & Sweeney, 2009; Pennington & Ozonoff, 1996). For instance, children with ADHD and EF deficits are more likely to show poorer achievement in school than children with ADHD who do not have EF deficits or non-ADHD controls with EF deficits (Biederman, et al., 2004). In a study of kindergarteners with ADHD that evaluated the relationship between academic skills (mathematics and language arts),
hyperactive/inattentive symptoms, and higher order cognitive abilities, poor academic achievement in children with ADHD was primarily mediated by EF deficits as opposed to delay aversion or hyperactivity/impulsivity (Thorell, 2007). A recent study examining the relationship between EF and category-learning performance in adults found that working memory capacity mediates category learning ability (Lewandowsky, 2011). Therefore, to the extent in which category learning is dependent on these cognitive processes, we might also expect category learning to be impaired in ADHD.

Though understanding the role of EF processes in the development of skilled performance is an important first step, much remains unknown about how cognitive skills are encoded, represented, and retained in children with ADHD. Given the functional significance of difficulties in these areas, it would be fruitful to explore the extent to which the mechanisms involved in these complex cognitive processes are operational in children with ADHD. Doing so will serve to better focus our efforts on selecting relevant means of academic remediation and tutelage.

Several lines of research suggest a potential deficit in feedback processing in children with ADHD. First, studies in ADHD populations examining the ameliorative effects of methylphenidate (Solanto, 1998; Vaidya, et al., 1998), volumetric abnormalities in the basal ganglia (Krain & Castellanos, 2006), DRD2 single nucleotide polymorphism analysis (Kollins, et al., 2008; Lasky-Su, et al., 2008), and functional differences in DA rich brain regions (Teicher, et al., 2000) provide ample support for the presence of dysfunctional DA network activity in the etiology of ADHD. Given DA’s critical role in reinforcement learning, it is plausible that such deficits might contribute directly to observed differences in skilled performance between children with and without ADHD.
Data from psychophysiological research currently support a critical role for feedback processing is impaired in children with ADHD (Shiels & Hawk Jr, 2010). For instance, cardiac responses to negative performance feedback that have been consistently found in children and adults (Crone, Jennings, et al., 2004; Crone, et al., 2003) in probabilistic learning paradigms are reduced in children with ADHD as evaluated in a time production task (Luman, Oosterlaan, Hyde, Van Meel, & Sergeant, 2007). Neuroimaging studies of post-error behavior changes show decreased BOLD signaling in the ACC during conflict tasks in children with ADHD as compared to non-ADHD controls (Bush, et al., 1999). Several between group event-related potentials studies in children on performance monitoring have shown reduced error-related negativities on Erikson flanker (Albrecht, et al., 2008; Van Meel, et al., 2007) and probabilistic learning (Groen, et al., 2008) tasks, or reduced error positivities on Flanker (Jonkman, et al., 2007) and Go/No-go tasks (Van De Voorde, Roeyers, & Wiersema, 2010; Wiersema, et al., 2005; Zhang, Wang, Cai, & Yan, 2009) in children with ADHD. Similar studies of error feedback monitoring have shown reduced post error feedback P2 during a probabilistic learning task (Groen, et al., 2008) and a fixed accuracy rate guessing game (Van Meel, Oosterlaan, Heslenfeld, & Sergeant, 2005). Interestingly, Althaus et al. (2009)found significant correlations between error positivity and parent report measures of inattention and hyperactivity problems in children with ADHD. Equivocal event-related potential (ERP) results regarding the precise deficit in feedback processing in ADHD may reflect the methodological issue of different tasks between studies that may differentially activate error processing networks, or the presence of true heterogeneity in the population. Regardless of where along the pathway the dysfunction exists, cumulative
evaluation of the psychophysiological literature strongly suggests the presence of impairment in some mechanism within the error feedback processing cognitive system to the extent that these impairments have been proposed as a potential endophenotype for ADHD (Albrecht, et al., 2008).

Research addressing feedback processing in ADHD has shown that individuals with ADHD show a decreased sensitivity to reinforcement contingencies on heart rate and skin conductance measures (Iaboni, Douglas, & Ditto, 1997), and a steeper and shorter waning effect of reinforcement (Sagvolden, Aase, Zeiner, & Berger, 1998). Although these studies suggest that feedback processing may be impaired in children with ADHD, results using post-error slowing as a behavioral measure of feedback processing have proven somewhat equivocal. Sergeant & Van der Meere (1988) were the first to study post-error slowing in children with ADHD. Using a display search task, they found that children with ADHD showed no change in post-error slowing across task difficulty whereas non-ADHD controls showed a significant increase in post-error slowing as working memory demands increased. These results suggest that impairments in post-error behavioral adjustment in children with ADHD might be related to impairments in executive functioning abilities, particularly in regard to problems with working memory. Post-error slowing behavior has also been evaluated in other executive domains including inhibitory control using the stop-signal reaction time (Schachar, et al., 2004) and Go/No-Go (Van De Voorde, et al., 2010; Wiersema, et al., 2005) paradigms. While results from Schachar, et al. (2004) and Wiersema et al. (2005) agreed with those from Sergeant & Van der Meere (1988), Van De Voorde, et al. (2010) found no significant impairment in post-error slowing in children with ADHD as compared to
controls. The lack of post-error slowing observed in Van De Voorde et al., (2010) may be due to the fact that, unlike the other studies, a response deadline was imposed as part of the task manipulation. Imposing a response deadline in performance monitoring studies may decrease the amount of post-error slowing across all groups, as slowing down too much would be maladaptive to the goal (Shiels & Hawk Jr, 2010). This experimental manipulation may have decreased the amount of post-error slowing observed in the control group as compared to that found in other studies. Such findings of reduced post-error slowing in the presence of a response deadline has been found support in another type of inhibitory control paradigm known as conflict monitoring tasks (Van Meel, et al., 2007). Conflict monitoring tasks tap processes involved in the suppression of inappropriate responses that are elicited by prevalent but irrelevant information (e.g., Flanker, Stroop) (Eriksen & Ericksen, 1974). In contrast to results using other inhibitory control tasks that support a post-error behavior modification impairment in ADHD, studies using conflict monitoring tasks generally have not found group differences between children with and without ADHD as a result of an absence in post-error slowing in both groups (Jonkman, et al., 2007; Van Meel, et al., 2007). However, it is important to note that no feedback regarding performance was provided in either of these studies. Given the high degree of response conflict present in these tasks, it is possible that children are unaware of the fact that they made a mistake on any given trial. Unlike the study where children were explicitly told to pay attention to when they make a mistake (Sergeant & Van der Meere, 1988), and the stop-signal reaction time study where an auditory stop-signal may have provided an alerting response to inhibition failures, errors
may be significantly harder to detect on conflict monitoring tasks, resulting in decreased post-error behavior modification.

Summary and Current Study

Previous research on error processing in ADHD has primarily focused on examining PES and error feedback processing in discrete reaction time tasks; none have evaluated its direct effect on learning or skill acquisition. As this process is essential to learning and academic success, it is imperative that we evaluate the functional purpose of error processing (as operationalized by post-error slowing) in the context of skill acquisition. Category learning is an exemplary paradigm by which to study this phenomenon because of its reliance on external feedback for the acquisition of skilled performance and notable working memory load requirements. Based on data from the available literature regarding alerting responses and developmental changes in post-error slowing in childhood, on screen feedback information will appear after each response and age will be assessed as a mediator for any observed post-error slowing effects.

I propose to examine the degree to which the health of the error monitoring system (as indexed by post-error slowing) predicts performance on an explicit category learning paradigm in college attending adults, typically developing children and children with ADHD. I expect to find significant group differences in which, compared to typically developing children, adults will perform with higher accuracy, faster reaction times, earlier and more consistent adoption of the correct sorting strategy, and accelerated learning rates. They will further show more robust effects of post-error slowing on performance gains as compared to typically developing children, indicating the presence
of developmental differences in the ability to use error feedback information in skill acquisition. In light of converging evidence from the psychophysiological and reinforcement learning literatures suggesting impaired skill acquisition as well as error processing deficits in childhood ADHD, I expect that children with ADHD will show lower accuracy, slower reaction times, later and less consistent use of the correct sorting strategy, and slower rates of skill acquisition compared to their age-matched, non-affected peers.

Though typically developing children will show less PES than college attending adults, it is expected that they will show more post-error slowing than children with ADHD, representing the presence of a dysfunctional ability in eliciting post-error behavioral adjustment. These between-group differences in PES will be related to accuracy and disparate abilities in “learning” the optimum categorization rule.

Methods

Participants

Adult participants are 38 adults between the ages of 18-25 (15 males) matriculating at the Pennsylvania State University. Child participants were 109 children between the ages of 8-12, identified as either ADHD (n = 59, 39 males) or control (n = 50, 23 males). Sample ethnicity will reflect regional demographics of 96% Caucasian. Children were recruited from the community and underwent a multistep screening process.
Exclusion criteria included: (1) current non-stimulant psychotropic medication treatment (e.g., neuroleptics, antidepressants), (2) previous diagnosis of pervasive developmental disorder, intellectual disability, sensorimotor disability, psychosis, or other parent-reported neurological disorder (e.g., traumatic brain injury, epilepsy), and (3) estimated full Scale IQ (FSIQ) values below 80. The initial screening phase included a brief parent phone interview to see if their child meet either of the first two exclusion criteria listed above. For those passing the phone screen, parents and the child’s primary teacher were mailed a short series of questionnaires regarding the child’s behavior including: BASC-2 (Reynolds & Kamphaus, 1992), the ADHD rating scale (DuPaul, Power, Anastopoulos, & Reid, 1998), and the Conner’s Rating Scale (Conners, 1997). Indices often associated with ADHD (BASC-2: hyperactivity, aggression, conduct problems, attention problems; Conner’s: oppositional problems, cognitive/inattention problems, hyperactivity, ADHD Index) were used to screen children as potentially ADHD and potentially non-ADHD control.

Identification of Children with ADHD. Children whose scores on the above named rating scales and indices exceeded the 85th percentile on at least one parent and one teacher scale were considered as potentially ADHD. Final diagnostic decisions were determined following DSM-IV including age of onset, duration, and impairment as determined by a structured clinical interview Diagnostic Interview Schedule for Children version IV (DISC-IV) (Shaffer, Fisher, & Lucas, 1997) administered to the child’s primary care giver by a trained research assistant. Following procedures provided by DSM-IV field trial data (Lahey, et al., 1994), an “or” algorithm integrating both parent and teacher reports of child behavior were used to determine final symptom count – a
symptom is reported as present if it was endorsed as occurring often or very often by either the parent on the DISC or teacher on the ADHD rating scale (DuPaul, et al., 1998). Children who have 5 symptoms of inattention or hyperactivity/impulsivity were also excluded due to ambiguities in subtype classification determination (Lahey, et al., 1994). Typically developing controls must have showed less than 4 total symptoms of ADHD according to the “or” algorithm based off parent DISC-IV and teacher ADHD rating scale reports.

All non-ADHD controls must have (1) scored below the 80th percentile on all ADHD relevant indices on both parent and teacher questionnaires, (2) showed less than 3 total symptoms of ADHD following the “or” algorithm, and (3) have never been diagnosed with ADHD in the past.

Children currently taking stimulant medication were asked to discontinue medication use for 24-48 hours prior to test day. Families were compensated for completing each phase of the screening and testing procedure.

**Diagnostic Questionnaires.**

*Behavioral Assessment Scale for Children (BASC-2).* The BASC-2 is an age-normed broad band scale covering a wide range of psychopathology grouped into externalizing problems (hyperactivity, aggression, conduct problems), internalizing problems (anxiety, depression, somatization), behavior symptoms index (atypicality, withdrawal, attention problems), and adaptive skills (adaptability, social skills, leadership, activities of daily living, functional communication) categories. Parent and teacher versions of the BASC will provide normative T score values on scales related to
ADHD such as Attention Problems, Hyperactivity, Aggression, and Oppositional Behavior. Standard cutoff values of scores exceeding the 85\textsuperscript{th} percentile, representing clinically significant behavioral difficulties, for ADHD relevant indicators endorsed by both parent and teacher will be used representing clinically significant behavioral difficulties. Median test-retest reliabilities for children on the BASC-2 are .86 for the teacher scale and .84 for the parent scale (Reynolds & Kamphaus, 1992).

\textbf{DuPaul ADHD Behavior Rating Scale.} Items on the scale are composed of the diagnostic criteria for ADHD in the DSM-IV. Parent or teacher endorsement of the presence of a symptom as either “often” or “very often” are included in the symptom count during the initial screening phase. Alpha coefficients for test-retest reliability is .94 for teacher ratings and .85 for parent ratings. Combined parent and teacher rating predictive validity for the inattention to an ADHD-I diagnosis is .72 and for the hyperactivity subscale to an ADHD-C diagnosis is .75 (DuPaul, et al., 1998).

\textbf{Conner’s Rating Scale.} The Conner’s is an age-normed narrow band scale primarily covering ADHD related behaviors that provides (1) an index for ADHD, (2) a total global index as well as ones for restlessness/impulsivity and emotional lability, and (3) a DSM-IV total index with subtype indices of DSM-IV Inattention and DSM-IV Hyperactivity-Impulsivity. Parent and teacher short form versions of the Conner’s Rating Scales will provide normative T score values on indices relevant to ADHD such as Cognitive/Inattentive Problems, Hyperactivity Problems, and ADHD index to be used in the participant screening process. Standard cutoff values of scores exceeding the 85\textsuperscript{th} percentile, representing clinically significant behavioral difficulties, for ADHD indicators endorsed by both parent and teacher will be used. Test-retest reliability coefficients range
from 0.57 to 0.85 on the parent long form and from 0.72 to 0.92 on the teacher short form (Conners, 1997).

**Procedures**

Children qualified to participate in the study were administered a neuropsychological battery conducted by trained study staff that included the tests described below.

**IQ.** Estimated full scale IQ (FSIQ) assessments were attained using an abbreviated form of the Weschler Intelligence Scale for Children (WISC-IV). The two subtest short form consists of the vocabulary and matrix reasoning subtests and has a test-retest reliability of 0.93 and a predictive validity value of 0.87 to results obtained from full battery assessment of IQ (Wechsler, 2003). Overall cumulative grade point average (GPA) was used as a proxy for IQ in the adult cohort.

**WMI.** The working memory index of the WISC-IV, composed of the digit span and letter-number sequencing subtests, were obtained. The two subtest index has a test-retest reliability of 0.85 (Wechsler, 2003).

**Categorization learning paradigm.** The stimuli and category structures are pictured in Figure 1. A categorization strategy following a fixed spatial frequency rule was selected. Using MATLAB routines, Gabor patch stimuli varying across spatial frequency and angular orientation were created to meet criteria for Category A (40) and Category B (40) (Maddox, et al., 2003). In this experimental design, angular orientation is an irrelevant dimension and must be ignored in order to achieve optimal performance. All participants received the same randomized order of stimuli appearance. The task was
Figure 1. Stimulus plot.

**A**

![Stimulus plot graph]

**B**

![Stimulus image]
divided into 5 blocks, each block consists of 80 trials (total 400 trials), with each patch appearing once per block. The task was self-paced. Visual feedback for accuracy (“correct” or “wrong”) was presented for 500msec after each trial (see Figure 2).

Participants were asked to determine whether they think the images presented on the screen should go in category “A” (corresponding to the z key) or category “B” (corresponding to the / key). Subjects were told that the computer will provide them with immediate feedback as to whether or not their selection was correct. Participants were instructed that, although they will just be guessing at first, at some point they may start to get an idea, or a “feeling,” about which images go into which category. Participants were instructed to go with their feeling, to be as accurate as possible, and not to be concerned with speed. After the instructions were provided, study staff removed themselves from the child’s line of vision. Task administration time was approximately 20 minutes in length.

Performance Measures

Reaction times and accuracy data were the dependent variables. All anticipatory reaction times (RT) less than 140msec were excluded from analysis because these reaction times have occurred too quickly to represent active decision making behavior in response to the stimulus (Eppinger, et al., 2009). For each block of 80 trials, a mean correct reaction time (CRT) was calculated by averaging the reaction times for correct trials that followed a correct trial. In contrast, for each block, the mean post-error reaction time (PERT) was calculated as the mean reaction time of the first correct response after an error. Post-error slowdown per block was considered in four ways: (1) PERT; (2)
Figure 2. Category learning paradigm
absolute PES = PERT – CRT; (3) proportional PES = PERT/CRT; (4) z-PES = abs PES/(SD CRT). Absolute PES, proportional PES, and z-PES were alternative means of assessing post-error slowdown designed to correct for generalized differences in reaction time regularly observed between ADHD and age-matched controls over a range of tasks (Leth-Steensen, King Elbaz, & Douglas, 2000).

A number of models were fit to each participant’s set of responses on a block by block basis. All of these models assumed that the participant set decision criteria along one or more stimulus dimensions that partitioned the stimulus space into verbalizable response regions. Each response region was assigned to a category (e.g., respond A if the line is thick). The location of each decision criterion is a free parameter. A general linear classifier model, which assumes that the decision bound between the categories is linear, was applied to the data, provides 3 parameters: slope, intercept of the linear bound, and noise. The “noise” parameter provides an estimate of the perceptual and criterial noise associated with classification. The model was fit using maximum likelihood procedures and BIC. Best fit lines depicting an individual’s pattern of responding were created for each block, and represent an approximation of the participant’s sorting criteria. Due to the manner in which the stimuli dimension characteristics were originally plotted, the optimal decision slope for this paradigm should approach infinity. For purposes of statistical analysis, an x,y transformation of the data was conducted. As a result, a slope of 0 constitutes the optimal decision bound for category selection.
Statistical Analyses

In all analyses, measures of IQ, WMI and demographic variables were used to control for overall cognitive functioning, executive control skills previously deemed important to skill acquisition, and to eliminate the role of other potentially relevant factors (gender, age).

Individual differences in category learning. Hypothesis 1: Children with ADHD will show impaired performance on skill acquisition, as indexed by lower accuracy and slower reaction time, compared to typically developing controls. College attending adults will in turn out perform typically developing children. If hypothesis 1 is true, then a significant main effect of group, block, and a 3 (group) x 5 (block) interaction on accuracy and reaction time in which adults outperform typically developing children, who in turn outperform children with ADHD would be expected. Significant group differences in the rate of skill acquisition as indexed by the slope of improvement for accuracy and reaction time would also be observed. *Post hoc* LSD contrasts would illustrate specific between group differences in which it would be expected that adults would outperform non-ADHD controls, who would in turn outperform children with ADHD. Single sample t-tests will be conducted for each block to ensure that accuracy rates are significantly different from random guessing (50%). Speed-accuracy trade-off effects, as defined by the presence of a negative correlation between reaction of correct responding and errors, will be assessed per block.

Individual differences in Post-Error Slowing. Hypothesis 2: Children with ADHD show less post-error slowing as compared to typically developing controls. College attending adults will in turn show more post-error slowing than typically
developing controls. If individuals differences in error processing exist among ADHD, typically developing children, and adults, a significant main effect of group, as well as a significant 3 (group) x 5 (block) interaction for post-error slowing – as measured via PERT, absolute PES, proportional PES, or z-PES – would be seen. One-way ANOVAs or single sample t-tests will be conducted for each block to test the degree to which (1) PERT differs from CRT, (2) absolute PES differs from 0, and (3) proportional PES differs from 1.

Individual differences in the association of post-error slowing to performance. Hypothesis 3: Adults will show more robust effects of post-error slowing on performance as compared to typically developing children who will in turn show stronger effects of post-error slowing on performance than children with ADHD. If post-error behavioral adjustments play a critical role in skill acquisition, then PES should predict accuracy as well as the adoption of the correct sorting strategy as determined by model-based analyses. Therefore, we expect to find a significant mediating effect of sorting strategy on the relationship between the four post-error slowing measures and performance. This analysis will be primarily evaluated for the initial block, where the largest amount of learning is expected to occur (Ashby, Maddox, & Bohil, 2002). A similar regression analysis will be conducted for data on typically developing controls and children with ADHD across the block in which the steepest learning slope is observed.
Results

Participants

According to parent and teacher report (DISC, ADHD-RS, BASC-2, CRS), children with ADHD had more symptoms of hyperactivity, impulsivity, and inattention as compared to controls (all $p < 0.001$, all $\sigma^2 > 0.38$; see Table 1). No significant group differences were found for age ($F(1,107)= 0.89, p = 0.35$, $\sigma^2 = 0.01$) or estimated IQ ($F(1,107)= 0.208, p = 0.65$, $\sigma^2 < 0.01$). However, a significant group difference in mean working memory capacity was observed as measured by the WISC-IV working memory index ($F(1,107)= 5.91, p = 0.02$, $\sigma^2 = 0.05$) (see Table 2). No significant effects of gender were found for any of the variables tested (all $p > 0.16$). No significant effect of age was found for IQ/GPA or WMI (all $p > 0.09$). Amongst children with and without ADHD, no significant effect of age was found for any of the variables tested (all $p > 0.65$).

Individual differences in skill acquisition

Speed-accuracy tradeoffs in responding were not observed; there was a significant positive correlation between correct and error RT for all groups (adults $r= 0.87, p < 0.001$; controls $r = 0.92, p < 0.001$; ADHD $r = 0.94, p < 0.001$). Additionally, there was a significant negative correlation of overall RT to number of errors for adults and children with ADHD (adults $r = -0.34, p = 0.04$; ADHD $r = -0.27, p = 0.04$), and no significant relationship was found for non-ADHD controls (controls $r = 0.09, p = 0.54$). It is therefore assumed that the data reflect adequate levels of effortful engagement throughout task administration and that RT and accuracy data can be validly interpreted.
Table 1. ADHD symptoms. Means, standard deviations, and statistics displayed.

<table>
<thead>
<tr>
<th></th>
<th>Control (N=50)</th>
<th>ADHD (N=59)</th>
<th>F(1,107), p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hyperactivity/Impulsivity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total # of symptoms</td>
<td>0.34 ± 0.56</td>
<td>4.44 ± 2.97</td>
<td>F = 92.27, p &lt; 0.001</td>
</tr>
<tr>
<td>Parent BASC-2 T score</td>
<td>43.14 ± 5.54</td>
<td>62.63 ± 12.78</td>
<td>F = 100.23, p &lt; 0.001</td>
</tr>
<tr>
<td>Parent Conners T score</td>
<td>46.16 ± 3.00</td>
<td>63.15 ± 12.69</td>
<td>F = 85.55, p &lt; 0.001</td>
</tr>
<tr>
<td>Teacher BASC-2 T score</td>
<td>43.00 ± 3.72</td>
<td>59.90 ± 11.79</td>
<td>F = 94.58, p &lt; 0.001</td>
</tr>
<tr>
<td>Teacher Conners T score</td>
<td>45.50 ± 2.58</td>
<td>58.97 ± 11.45</td>
<td>F = 66.18, p &lt; 0.001</td>
</tr>
<tr>
<td><strong>Inattentive symptoms</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total # of symptoms</td>
<td>0.70 ± 0.99</td>
<td>7.92 ± 1.37</td>
<td>F = 959.78, p &lt; 0.001</td>
</tr>
<tr>
<td>Parent BASC-2 T score</td>
<td>43.60 ± 5.87</td>
<td>65.95 ± 6.02</td>
<td>F = 381.76, p &lt; 0.001</td>
</tr>
<tr>
<td>Parent Conners T score</td>
<td>45.58 ± 3.52</td>
<td>69.00 ± 11.52</td>
<td>F = 191.27, p &lt; 0.001</td>
</tr>
<tr>
<td>Teacher BASC-2 T score</td>
<td>42.56 ± 6.03</td>
<td>60.97 ± 6.82</td>
<td>F = 218.98, p &lt; 0.001</td>
</tr>
<tr>
<td>Teacher Conners T score</td>
<td>46.36 4.54</td>
<td>60.32 ± 11.69</td>
<td>F = 63.20, p &lt; 0.001</td>
</tr>
</tbody>
</table>
Table 2. Demographic data. Means, standard deviations. Significance results for one-way ANOVAs between child groups on IQ, working memory, and age.

<table>
<thead>
<tr>
<th></th>
<th>Adults (N=38)</th>
<th>Control (N=50)</th>
<th>ADHD (N=59)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
<td>19.11 ± 0.24</td>
<td>10.44 ± 1.26</td>
<td>10.14 ± 1.32</td>
</tr>
<tr>
<td><strong>Males</strong></td>
<td>15</td>
<td>23</td>
<td>39</td>
</tr>
<tr>
<td><strong>IQ</strong></td>
<td>N/A</td>
<td>104.02 ± 9.22</td>
<td>103.0 ± 13.32</td>
</tr>
<tr>
<td><strong>GPA</strong></td>
<td>3.32 ± 0.10</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>WMI</strong></td>
<td>N/A</td>
<td>102.60 ± 10.97*</td>
<td>96.83 ± 13.40*</td>
</tr>
</tbody>
</table>
**Accuracy.** Single sample t-tests indicate that accuracy rates for all groups in all blocks was significantly better than chance (50% accuracy) except for children with ADHD in block 2 who were performing at chance levels.

Group differences in accuracy were observed (omnibus $F(2,144) = 39.38$, $p < 0.001$, $\eta^2 = 0.35$), where, on average, adults showed greater accuracy than both controls and children with ADHD (both post hoc contrasts $p < 0.003$), and controls showed greater accuracy than children with ADHD (post hoc contrast $p = 0.001$). A main effect of block on accuracy was also observed ($F(4,576) = 47.13$, $p < 0.001$, $\eta^2 = 0.25$). Planned contrasts indicated that the effect of block was linear ($F(1,144) = 100.39$, $p < 0.001$, $\eta^2 = 0.41$) with accuracy increasing over time (see Table 3 and Figure 3a).

The main effects were followed by a significant Group x Block interaction ($F(8,576) = 8.64$, $p < 0.001$, $\eta^2 = 0.11$). Post hoc pair-wise comparisons found significant linear group x block interactions for adults vs. controls ($F(1,86) = 11.45$, $p = 0.001$, $\eta^2 = 0.12$), and for adults vs. ADHD ($F(1,95) = 30.73$, $p < 0.001$, $\eta^2 = 0.24$). Analyses of slope confirmed that adults displayed a steeper accuracy slope than did either group of children (adults-controls, $p = 0.001$; adults-ADHD, $p < 0.001$; see Table 4). Significant Group x Block interactions were also observed between children with and without ADHD, ($F(4,428) = 3.45$, $p = 0.009$, $\eta^2 = 0.31$, in which controls demonstrated a steeper accuracy curve over children with ADHD ($p = 0.048$, see Table 5).

**Correct Reaction Time (CRT).** As with accuracy-based analyses, there was a main effect of Group on CRT ($F(2,144) = 6.41$, $p = 0.002$, $\eta^2 = 0.08$). Post hoc contrasts revealed that adults were faster than both controls ($p = 0.004$, $\eta^2 = 0.09$) and children with ADHD ($p < 0.001$, $\eta^2 = 0.14$), who did not differ from one another ($p = \ldots$)
Table 3: Percent Accuracy and correct reaction time (CRT) across block. Means and standard errors.

<table>
<thead>
<tr>
<th></th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Block 4</th>
<th>Block 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults (n=38)</td>
<td>64.01 ± 1.99</td>
<td>72.56 ± 2.54</td>
<td>77.85 ± 2.56</td>
<td>81.92 ± 2.10</td>
<td>82.53 ± 1.93</td>
</tr>
<tr>
<td>Control (n=50)</td>
<td>56.25 ± 1.82</td>
<td>61.25 ± 2.29</td>
<td>64.46 ± 2.17</td>
<td>63.73 ± 2.36</td>
<td>65.59 ± 2.44</td>
</tr>
<tr>
<td>ADHD (n=59)</td>
<td>52.90 ± 1.04</td>
<td>51.97 ± 1.32</td>
<td>54.98 ± 1.49</td>
<td>54.52 ± 1.55</td>
<td>57.40 ± 1.54</td>
</tr>
<tr>
<td><strong>Correct RT (ms)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults (n=38)</td>
<td>1335 ± 121</td>
<td>1209 ± 101</td>
<td>1021 ± 54</td>
<td>919 ± 33</td>
<td>903 ± 38</td>
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<tr>
<td>Control (n=50)</td>
<td>1555 ± 99</td>
<td>1432 ± 93</td>
<td>1554 ± 167</td>
<td>1549 ± 142</td>
<td>1373 ± 152</td>
</tr>
<tr>
<td>ADHD (n=59)</td>
<td>1529 ± 111</td>
<td>1793 ± 152</td>
<td>1663 ± 133</td>
<td>1458 ± 107</td>
<td>1424 ± 112</td>
</tr>
</tbody>
</table>
Figure 3. Accuracy & Correct Reaction Time across block.

A

**Accuracy**

```
0.40 0.50 0.60 0.70 0.80 0.90 1.00
1 2 3 4 5
```

B

**Correct RT**

```
0.60 0.80 1.00 1.20 1.40 1.60 1.80 2.00 2.20
1 2 3 4 5
```
Table 4. Learning Curve slope analyses. Means, standard errors, and $p$ values from post-hoc pair-wise comparisons.

<table>
<thead>
<tr>
<th></th>
<th>Adults (N=38)</th>
<th>Controls (N=50)</th>
<th>ADHD (N=59)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acc slope</td>
<td>0.037 ± 0.024\textsuperscript{a}</td>
<td>0.019 ± 0.029\textsuperscript{b}</td>
<td>0.009 ± 0.023\textsuperscript{c}</td>
</tr>
<tr>
<td>CRT slope</td>
<td>-0.086 ± 0.142\textsuperscript{a}</td>
<td>-0.037 ± 0.165\textsuperscript{a}</td>
<td>-0.021 ± 0.183\textsuperscript{a}</td>
</tr>
</tbody>
</table>

Different superscripts represent significant between group differences. Same superscripts represent the absence of significant group differences.
Table 5: Analysis of Group and Block effects. Omnibus $F$ and $\eta^2_p$ values for all measures of reaction time.

<table>
<thead>
<tr>
<th></th>
<th>Accuracy</th>
<th>Error RT</th>
<th>CRT</th>
<th>PERT</th>
<th>Abs PES</th>
<th>Prop PES</th>
<th>z PES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main effects</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block</td>
<td>$\text{F}(4,576)=47.13^*$</td>
<td>$\text{F}(4,576)=3.65^*$</td>
<td>$\text{F}(4,576)=5.18^*$</td>
<td>$\text{F}(4,576)=5.63^*$</td>
<td>$\text{F}(4,576)=1.27$</td>
<td>$\text{F}(4,576)=2.76^\dagger$</td>
<td>$\text{F}(4,576)=4.06^*$</td>
</tr>
<tr>
<td></td>
<td>$\eta^2_p=0.25$</td>
<td>$\eta^2_p=0.03$</td>
<td>$\eta^2_p=0.04$</td>
<td>$\eta^2_p=0.04$</td>
<td>$\eta^2_p=0.01$</td>
<td>$\eta^2_p=0.02$</td>
<td>$\eta^2_p=0.03$</td>
</tr>
<tr>
<td>Group</td>
<td>$\text{F}(2,144)=39.38^*$</td>
<td>$\text{F}(2,144)=2.30$</td>
<td>$\text{F}(2,144)=6.41^*$</td>
<td>$\text{F}(2,144)=6.39^*$</td>
<td>$\text{F}(2,144)=1.21$</td>
<td>$\text{F}(2,144)=2.00$</td>
<td>$\text{F}(2,144)=1.28$</td>
</tr>
<tr>
<td></td>
<td>$\eta^2_p=0.35$</td>
<td>$\eta^2_p=0.03$</td>
<td>$\eta^2_p=0.08$</td>
<td>$\eta^2_p=0.08$</td>
<td>$\eta^2_p=0.02$</td>
<td>$\eta^2_p=0.03$</td>
<td>$\eta^2_p=0.02$</td>
</tr>
<tr>
<td>Interaction</td>
<td>$\text{F}(8,576)=8.64^*$</td>
<td>$\text{F}(8,576)=1.66$</td>
<td>$\text{F}(8,576)=2.42^\dagger$</td>
<td>$\text{F}(8,576)=2.34^\dagger$</td>
<td>$\text{F}(8,576)=1.43$</td>
<td>$\text{F}(8,576)=0.88$</td>
<td>$\text{F}(8,576)=0.79$</td>
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<tr>
<td></td>
<td>$\eta^2_p=0.11$</td>
<td>$\eta^2_p=0.11$</td>
<td>$\eta^2_p=0.03$</td>
<td>$\eta^2_p=0.03$</td>
<td>$\eta^2_p=0.02$</td>
<td>$\eta^2_p=0.01$</td>
<td>$\eta^2_p=0.01$</td>
</tr>
</tbody>
</table>

*p<0.01 †p<0.05
A main effect of Block was also observed ($F(4,576) = 5.18, p < 0.001$, $\eta^2 = 0.04$) in which RT decreased over blocks of trials ($F(1,144) = 5.98, p < 0.001$, $\eta^2 = 0.09$) (see Figure 3b).

Main effects were followed by a significant Group x Block interaction ($F(8,576) = 2.42, p = 0.01$, $\eta^2 = 0.03$). Pair-wise comparisons found a significant linear Group x Block interactions for adults vs. non-ADHD controls ($F(4,344) = 3.42, p = 0.01$, $\eta^2 = 0.04$), but there were no group differences in slope ($p = 0.17$). No significant interactions were found between controls and children with ADHD ($F(4,428) = 2.17, p = 0.07$, $\eta^2 = 0.02$) or between adults and children with ADHD ($F(4,380) = 2.15, p = 0.07$, $\eta^2 = 0.02$).

**Individual differences in Post-Error Slowing**

Among the four measures of post-error slowing, significant group differences averaged over blocks of trials were only observed for PERT ($F(2,144) = 6.39, p = 0.002$, $\eta^2 = 0.08$; all other measures of PES: all $p > 0.1$, all $\eta^2 < 0.02$; see Figure 4 and Table 6). Adults showed less PERT than either controls or children with ADHD (all $p < 0.01$, $\eta^2 > 0.09$) who did not differ from one another ($p = 0.23$, $\eta^2 = 0.01$). Analyses conducted on the block where most learning was expected to occur (block 1) showed no group differences in any of the four measures of PES (all $p > 0.09$, all $\eta^2 < 0.03$).

A significant main effect of Block was found for PERT ($F(4,576) = 5.63, p < 0.001$, $\eta^2 = 0.04$), proportional PES ($F(4,576) = 2.76, p = 0.03$, $\eta^2 = 0.02$), and z-PES ($F(4,576) = 4.06, p = 0.003$, $\eta^2 = 0.03$) in which PES decreased over time. There was no Block effect for absolute PES ($F(4,576) = 1.27, p = 0.28$, $\eta^2 = 0.01$; see Figure 4A & B and Table 6).
Figure 4. Post-error Slowing across block.

A

Post Error RT
Avg RT of the first correct response after an error

B

Absolute PES
PERT - CRT
(evaluation criteria > 0)
Figure 4 (cont’d). Post-error Slowing across block.

C  Proportional PES
PERT / CRT
(evaluation criteria > 1)

D  z-Score PES
absPES / SD CRT
(evaluation criteria > 1)

Adults

Controls

ADHD
Table 6: Post-error slowing across block as measured by the raw RT value for the first correct response after an error (PERT), the absolute difference in PERT and CRT, the proportional relationship between PERT to CRT, and the z-score of PERT in relation to an individuals’ observed CRT variability. Means, standard errors, and p values from individual t-tests (boundary value for PERT > CRT; abs PES > 0; prop PES > 1; z-PES > 1).

<table>
<thead>
<tr>
<th></th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Block 4</th>
<th>Block 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PERT (msec)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults (n=38)</td>
<td>1488 ± 110*</td>
<td>1156 ± 114</td>
<td>1036 ± 79</td>
<td>918 ± 40</td>
<td>889 ± 46</td>
</tr>
<tr>
<td>Control (n=50)</td>
<td>1534 ± 87</td>
<td>1421 ± 108</td>
<td>1385 ± 81</td>
<td>1403 ± 102</td>
<td>1350 ± 146</td>
</tr>
<tr>
<td>ADHD (n=59)</td>
<td>1592 ± 87</td>
<td>1602 ± 136</td>
<td>1801 ± 193</td>
<td>1496 ± 141</td>
<td>1457 ± 127</td>
</tr>
<tr>
<td><strong>abs PES (msec)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults (n=38)</td>
<td>153 ± 74*</td>
<td>-53 ± 56</td>
<td>16 ± 55</td>
<td>0 ± 29</td>
<td>-14 ± 32</td>
</tr>
<tr>
<td>Control (n=50)</td>
<td>-22 ± 77</td>
<td>-11 ± 57</td>
<td>-169 ± 120</td>
<td>-147 ± 79</td>
<td>-22 ± 37</td>
</tr>
<tr>
<td>ADHD (n=59)</td>
<td>63 ± 80</td>
<td>-191 ± 108</td>
<td>138 ± 123</td>
<td>37 ± 117</td>
<td>33 ± 77</td>
</tr>
<tr>
<td><strong>prop PES</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults (n=38)</td>
<td>1.16 ± 0.05*</td>
<td>0.97 ± 0.03</td>
<td>1.02 ± 0.04</td>
<td>1.01 ± 0.03</td>
<td>0.99 ± 0.03</td>
</tr>
<tr>
<td>Control (n=50)</td>
<td>1.02 ± 0.04</td>
<td>1.00 ± 0.04</td>
<td>0.99 ± 0.04</td>
<td>0.95 ± 0.03</td>
<td>1.00 ± 0.03</td>
</tr>
<tr>
<td>ADHD (n=59)</td>
<td>1.13 ± 0.05*</td>
<td>0.96 ± 0.05</td>
<td>1.07 ± 0.06</td>
<td>1.09 ± 0.09</td>
<td>1.07 ± 0.05</td>
</tr>
<tr>
<td><strong>z PES</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults (n=38)</td>
<td>0.39 ± 0.14</td>
<td>0.01 ± 0.08</td>
<td>0.07 ± 0.10</td>
<td>0.08 ± 0.08</td>
<td>0.04 ± 0.08</td>
</tr>
<tr>
<td>Control (n=50)</td>
<td>0.15 ± 0.09</td>
<td>0.03 ± 0.07</td>
<td>0.02 ± 0.07</td>
<td>-0.04 ± 0.06</td>
<td>0.06 ± 0.07</td>
</tr>
<tr>
<td>ADHD (n=59)</td>
<td>0.28 ± 0.10</td>
<td>0.07 ± 0.10</td>
<td>0.09 ± 0.07</td>
<td>0.25 ± 0.13</td>
<td>0.08 ± 0.06</td>
</tr>
</tbody>
</table>

*significant amounts of post-error slowing p<0.05
A significant Group x Block interaction effect was found for PERT ($F(8,576) = 2.34, \ p = 0.02, \ \hat{\eta}^2 = 0.03$; interaction effect for all other measures of PES were not significant: all $p > 0.1$, all $\hat{\eta}^2 < 0.02$) in which adults showed a trend of decreasing PERT over time that was not observed in non-ADHD controls ($F(4,344) = 9.21, \ p < 0.001, \ \hat{\eta}^2 = 0.10$) or in children with ADHD ($F(4,380) = 5.141, \ p < 0.001, \ \hat{\eta}^2 = 0.05$). No significant Group x Block interaction effects were observed in all other planned post hoc pair-wise comparisons for the remaining post-error slowing measures (all $p > 0.1$, all $\hat{\eta}^2 < 0.02$). Single-sample t-tests of absolute PES for all groups across all blocks indicate that, on average, only adults in block 1 show significant (i.e. $> 0$) amounts of post-error slowing ($t(37) = 2.07, \ p = 0.05$). Similar results were obtained when evaluating the degree to which average proportional PES was significantly different from 1 ($\text{PES} = \text{CRT}$) ($t(37) = 3.04, \ p = 0.004$) although this measure also showed that children with ADHD had significant post-error slowing as well ($t(58) = 2.80, \ p = 0.01$).

**Individual differences in the association of post-error slowing to performance: accuracy**

**Adults.** Evaluations of whether or not post error slowing was predictive of accuracy produced a significant positive relationship in block 1 accuracy for absolute PES ($r^2 = 0.12, \ p = 0.03$), and proportional PES ($r^2 = 0.10, \ p = 0.02$). No significant relationship was found between block 1 accuracy and block 1 PERT ($r^2 = 0.06, \ p = 0.15$) or z-PES ($r^2 = 0.05, \ p = 0.17$; see Tables 7 & 8, Figure 5). For all other blocks, there were significant positive relationships of accuracy in: block 3 for absolute PES ($r^2 = 0.12, \ p = 0.04$); block 4 for PERT ($r^2 = 0.16, \ p = 0.01$), absolute PES ($r^2 = 0.10, \ p = 0.05$), and proportional PES ($r^2 = 0.10, \ p = 0.05$); block 5 for PERT ($r^2 = 0.12, \ p = 0.04$). All other
Table 7: Relationship between PES and accuracy/sorting strategy. Regressions conducted by group by block, $r^2$ and $p$ values provided.

<table>
<thead>
<tr>
<th>Block</th>
<th>Adults (N=38)</th>
<th>Control (N=50)</th>
<th>ADHD (N=59)</th>
<th>Adults (N=38)</th>
<th>Control (N=50)</th>
<th>ADHD (N=59)</th>
<th>Adults (N=38)</th>
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<tbody>
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<td></td>
<td>Accuracy</td>
<td>Sorting Strategy</td>
<td></td>
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<td>Sorting Strategy</td>
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<tr>
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<td>0.14†</td>
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<td>0.03</td>
<td>0.12†</td>
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<td>0.02</td>
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<td>0.10†</td>
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<td>0.04</td>
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<td>0.17*</td>
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<td>0.10†</td>
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<tr>
<td>Adults (N=38)</td>
<td>0.12†</td>
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<td>0.02</td>
<td>0.01</td>
<td>0.14†</td>
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<td>0.08</td>
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<tr>
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<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>&lt;0.01</td>
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*p<0.01 †p<0.05
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<thead>
<tr>
<th></th>
<th>PERT</th>
<th>Abs PES</th>
<th>Prop PES</th>
<th>z-PES</th>
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<td></td>
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<tr>
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<td>B1⁺, B3⁺, B4⁺</td>
<td>B1⁺, B4⁺</td>
<td></td>
</tr>
<tr>
<td>Control (N=50)</td>
<td>B3⁺</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADHD (N=59)</td>
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<td>B1</td>
<td>B1</td>
<td>B1</td>
</tr>
<tr>
<td><strong>Sorting Strategy</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Adults (N=38)</td>
<td>B4⁺, B5⁺</td>
<td>B1⁺</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (N=50)</td>
<td>B1, B2</td>
<td></td>
<td>B2</td>
<td></td>
</tr>
<tr>
<td>ADHD (N=59)</td>
<td>B3</td>
<td>B3</td>
<td>B1, B3</td>
<td></td>
</tr>
</tbody>
</table>

+ prediction in the expected direction
Figure 5. Relationship between block 1 PES and block 1 accuracy

[Graphs showing the relationship between PERT, absolute PES, proportional PES, and z-score PES with block 1 accuracy for different groups (Control, ADHD (all subtypes), ADHD (DC: L-H: C), ADHD (DC: L: H-C), ADHD (DC: L: H-C), and ADHD (DC: L-H: C)). Each graph includes regression lines with corresponding R² values.]
analyses between post-error slowing and accuracy were non-significant (all $r^2 < 0.05, p > 0.05$).

**Controls.** In contrast to adults, there was no significant relationship between block 1 accuracy and block 1 post-error slowing (all $r^2 < 0.07, all p > 0.05$). However, there was a significant positive relationship in block 3 where absolute PES predicted block 3 accuracy ($r^2 = 0.08, p = 0.05$). All other analyses between post-error slowing and accuracy were non-significant (all $r^2 < 0.05, p > 0.05$).

**ADHD.** In children with ADHD, there was a significant negative relationship between block 1 accuracy and block 1 absolute PES ($r^2 = 0.07, p = 0.05$), proportional PES ($r^2 = 0.10, p = 0.02$), and z-PES ($r^2 = 0.09, p = 0.02$). No significant predictive relationship was found between block 1 accuracy and PERT ($r^2 = 0.001, p = 0.84$).

Evaluation of all other blocks indicated significant positive relationships between block 2 accuracy and block 2 PERT ($r^2 = 0.11, p = 0.01$), as well as for block 4 accuracy and block 4 PERT ($r^2 = 0.11, p = 0.01$). All other analyses between post-error slowing and accuracy were non-significant (all $r^2 < 0.05, all p > 0.05$).

**IQ and working memory.** Overall accuracy was positively related to estimated measures of IQ for non-ADHD controls ($r^2 = 0.08, p = 0.05$) but not for children with ADHD ($r^2 = 0.03, p = 0.18$). Overall accuracy was not related to GPA in adults. Overall accuracy was not related to estimated measures of working memory for either group of children (all $r^2 < 0.03, all p > 0.2$).

**Individual differences in the association of post-error slowing to performance: sorting strategy**
Adults. To evaluate the relationship between post-error behavior and the acquisition of the correct sorting strategy, the ability for post-error slowing to predict such strategy use was examined. If post-error slowing were in fact to predict sorting strategy, a significant negative association with the slope of the individual’s sorting strategy decision bound would be expected. No significant relationship was found between any measure of post-error slowing and the ability to acquire the correct sorting strategy in block 1 (all $r^2 < 0.10$, all $p > 0.05$; see Tables 7 & 8, Figure 5). For all other blocks, a significant negative relationship between the ability to acquire the correct rule-based sorting category and post-error slowing was observed in: block 4 for PERT ($r^2 = 0.13$, $p = 0.02$); block 5 for PERT ($r^2 = 0.14$, $p = 0.02$). All other analyses between post-error slowing and model use were non-significant (all $r^2 < 0.05$, $p > 0.05$).

Controls. In contrast to the negative relationship found in block 1 in adults, a significant positive relationship between block 1 sorting strategy and block 1 PERT was observed ($r^2 = 0.15$, $p = 0.01$) in which greater PERT was more likely to predict sorting along the irrelevant category. No significant predictive relationship was found between the ability to acquire the correct rule-based sorting category in block 1 and all other measures of post-error slowing (all $r^2 < 0.03$, all $p > 0.05$). Similar positive relationships were obtained for in block 2 for PERT ($r^2 = 0.31$, $p < 0.001$), and absolute PES ($r^2 = 0.11$, $p = 0.02$). All other analyses between post-error slowing and model use were non-significant (all $r^2 < 0.05$, $p > 0.05$).

ADHD. In children with ADHD, a significant positive relationship between block 1 sorting strategy and block 1 z-PES was observed ($r^2 = 0.08$, $p = 0.03$) in which greater z-PES was more likely to predict sorting along the irrelevant category. No significant
predictive relationship was found between block 1 sorting strategy and all other measures of PES (all $r^2 < 0.03$, all $p > 0.05$). Evaluation of all other blocks indicated significant positive relationships between block 3 model use and block 3 absolute PES ($r^2 = 0.16$, $p = 0.002$), proportional PES ($r^2 = 0.17$, $p = 0.001$), and z-PES (all $r^2 = 0.13$, all $p = 0.01$). All other analyses between PES and accuracy were non-significant (all $r^2 < 0.05$, all $p > 0.05$)

**Individual differences in the association of post-error slowing to performance: the mediating effect of post-error slowing on accuracy via sorting strategy model**

Evaluations of whether or not the effects of post-error slowing on accuracy were mediated by the ability for the individual to acquire the proper decision bound for categorization were conducted. Only the relationships that had significant positive within block post-error slowing to accuracy associations were assessed (see Table 9 and Figure 6).

**Adults.** Model use predicted accuracy in all blocks (see Model use predicting accuracy). PERT in blocks 4 and 5, and absolute PES in block 1 were no longer predictive of accuracy once sorting strategy was entered into the model (all $\Delta r^2 < 0.08$, all $p > 0.05$). Sorting strategy continued to predict accuracy even after controlling for absolute PES in block 1 ($\Delta r^2 = 0.25$, $\Delta p = 0.001$, $r^2 = 0.37$, $p < 0.001$) and PERT in blocks 4 ($\Delta r^2 = 0.12$, $\Delta p = 0.02$, $r^2 = 0.28$, $p = 0.004$) and 5 ($\Delta r^2 = 0.42$, $\Delta p < 0.001$, $r^2 = 0.53$, $p < 0.001$). Thus, model use significantly mediated the association between these indices of post-error slowing and accuracy in adults.
Table 9: Sorting strategy predicting accuracy by block. Regressions conducted by group by block, $r^2$ and $p$ values provided.

<table>
<thead>
<tr>
<th>Group</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Block 4</th>
<th>Block 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adults (N=38)</td>
<td>$r^2=0.35$</td>
<td>$r^2=0.34$</td>
<td>$r^2=0.28$</td>
<td>$r^2=0.21$</td>
<td>$r^2=0.53$</td>
</tr>
<tr>
<td></td>
<td>$p &lt; 0.001$</td>
<td>$p &lt; 0.001$</td>
<td>$p=0.001$</td>
<td>$p=0.003$</td>
<td>$p &lt; 0.001$</td>
</tr>
<tr>
<td>Control (N=50)</td>
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<td>$r^2=0.09$</td>
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<td>$r^2=0.18$</td>
</tr>
<tr>
<td></td>
<td>$p=0.23$</td>
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<td>$p=0.002$</td>
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<tr>
<td>ADHD (N=59)</td>
<td>$r^2=0.003$</td>
<td>$r^2=0.01$</td>
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</tr>
<tr>
<td></td>
<td>$p=0.68$</td>
<td>$p=0.59$</td>
<td>$p=0.44$</td>
<td>$p=0.33$</td>
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</tr>
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</table>
Figure 6. Relationships between block 1 PES and block 1 sorting strategy
**Controls.** Sorting strategy predicted accuracy in block 2 ($r^2 = 0.09, p = 0.04$), block 3 ($r^2 = 0.19, p = 0.002$), block 4 ($r^2 = 0.10, p = 0.03$), and block 5 ($r^2 = 0.18, p = 0.003$). Absolute PES in block 3 continued to explain significant amounts of variance in block 3 accuracy even after the variance associated with sorting strategy was removed ($\Delta r^2 = 0.10, \Delta p = 0.02, r^2 = 0.29, p < 0.001$). Thus, there was no evidence that sorting strategy mediated the relationship between post-error slowing and accuracy.

**ADHD.** In contrast to findings from controls, the measure of sorting strategy did not predict accuracy in any block (all $r^2 < 0.06$, all $p > 0.06$). The association of PERT in blocks 2 and 4 remained significant even after sorting strategy was entered into the model (block 2: $\Delta r^2 = 0.12, \Delta p = 0.01, r^2 = 0.13, p = 0.02$; block 4: $\Delta r^2 = 0.10, \Delta p = 0.02, r^2 = 0.12, p = 0.03$). As with non-ADHD controls, there was no evidence that sorting strategy mediated the relationship between post-error slowing and accuracy.

**Discussion**

Previous studies have provided some evidence regarding a deficit in error-feedback monitoring in children with ADHD (Albrecht, et al., 2008; Sergeant & Van der Meere, 1988; Wiersema, et al., 2005). A deficit in this skill may contribute to many of the behaviors we frequently see in ADHD including poor decision making (Luman, et al., 2008), decreased responsiveness to future consequences (Aase & Sagvolden, 2006), and an inability to modify behavior to environmental demands (Aase & Sagvolden, 2005). The previous studies measuring error processing in terms of post error behavior modification (e.g., post-error slowing) in ADHD were primarily conducted in speeded reaction time tasks. There is currently a gap in the literature on the study of error
processing in skill acquisition – an area where error processing theoretically plays a very prominent role. Studies have consistently found feedback to positively influence learning (Metcalfe & Kornell, 2007), and a deficit in ability to adjust future behavior in response to error feedback may be particularly detrimental to school-aged children who are frequently bombarded with new information across their many learning environments and who are regularly provided with external feedback regarding their performance. Studies examining error processing in skill acquisition would serve to determine the degree to which error processing is critical to learning in childhood, and would also contribute to the field’s current understanding of the academic difficulties frequently seen in children with ADHD. To this end, this study used a category learning task to examine differences in skill acquisition as a function of post error slowing in adults, typically developing children and in children with ADHD.

**Skill Acquisition in a Categorization Learning Paradigm**

The learning paradigm used in this study was a perceptual, rule-based categorization learning task that has been frequently evaluated in adults and is best approached via a declarative, hypothesis testing strategy (Ashby, Isen, & Turken, 1999; Ashby, et al., 2002; Maddox, Aparicio, Marchant, & Ivry, 2005). Results showed differences in achieved accuracy between adults, typically developing controls, and children with ADHD for this task. All groups displayed a general trend of increasing accuracy over time, with adults showing a steeper learning curve than control children, who in turn had a steeper learning curve than children with ADHD. This particular categorization learning paradigm proved to be relatively difficult, with adults achieving
an average of 83% accuracy by the final block, control children ultimately obtaining an average of 66% accuracy, and children with ADHD reaching, on average, only 58% accuracy. Despite this, it is clear that learning occurred in all groups as average accuracy values were consistently above that of guessing by block 3. As a further indication of increasing mastery, adults showed a pattern of decreasing reaction time in step with their increased accuracy across block. This pattern was not seen in either group of children, who showed no significant change in correct reaction time over block, again showing that mastery of this task was significantly more difficult for children than for adults.

These results generally match what we would expect given what is known about the course of cognitive development. As mentioned above, the task used in this study is relatively difficult; the stimuli and its categorization characteristics are fairly abstract and subtle. The presence of over-generalized category representations (Mareschal, et al., 2002; Minda, et al., 2008) and an increased propensity to group things by commonalities over differences (Gentner & Namy, 1999; Hammer, et al., 2009) likely make this task significantly more difficult for children as compared to adults. Furthermore, the cognitive process of hypothesis testing taps a number of executive functions including working memory, planning, and set-shifting abilities (Nomura, Maddox, & Filoteo, 2007; Schnyer, et al., 2009). It is fairly well established that working memory and other higher order executive abilities continue to develop into early adulthood (Bunge & Zelazo, 2006; Casey, et al., 2000; Cepeda, Kramer, & Gonzalez de Sather, 2001), giving adults an advantage in terms of the raw computing power required to achieve maximal accuracy in many tasks. As this particular study did not include a neuropsychological battery assessing cognitive functioning in adults, whether or not age-related improvements in EF
explained group differences in accuracy could not be empirically demonstrated. Although differences in working memory abilities were found between children with and without ADHD, accuracy was unrelated to working memory capacity both within and between either group of children. This may be attributable to the fact that both groups showed index values well within the normal range. The WM index score from the WISC-IV is an age-normed battery that does not lend to the interpretation of raw working memory capacity, just whether or not children fall within the average range of working memory abilities as compared to their age-matched peers. As a result, subtle differences in working memory ability become lost in the index measure. To determine the proportion of variance in accuracy that is attributable to these other cognitive processes involved in task mastery, future studies may consider administering a non-age-normed neuropsychological battery that would differentiate raw executive computing power between children and adults to further elucidate their developmental and potentially discriminatory roles in acquiring skillfulness in this type of abstract category learning task. Additionally, neurophysiological measures of frontal lobe activation using a learning paradigm could be used to further elucidate the strength of the association between PES and the recruitment of higher order cognitive processes.

**Measures of Post-error Slowing**

To assess for the presence of behavioral changes in response to error feedback, post-error slowing was measured four ways. Raw reaction time after an error (PERT) was the only measure of post-error slowing that showed significant between group differences, with adults showing smaller PERT than either group of children who did not
differ from each other. As PERT is a raw reaction time measure, these results are likely due to the fact that adults have faster RTs than children (Kail, 1991; Kail & Miller, 2006). Studies looking at the developmental course of processing speed have shown linear, global improvement in reaction time across a variety of motor, perceptual, and cognitive tasks over time (Kail, 1991). Similar to these previous findings, the group differences in PERT probably reflect a general increase in raw processing speed as opposed to a difference in the cognitive mechanism under review here (Kail, 2007).

Why PERT decreased over time in adults is unclear. A less interesting answer might simply be that it reflects the general decrease in reaction time that is typical of increased task mastery (Logan, 1988; Shiffrin & Schneider, 1977). A more interesting hypothesis would be that post-error slowing reactivity decreases with increasing task mastery. Some neurophysiological evidence involving ERP studies have demonstrated decreased amplitude in the waveforms associated with post-error processing as participants become increasingly adapted to speeded reaction time tasks. These studies, however, either reported no significant change in reaction time over the course of the task period or did not assess for such differences (Anguera, Seidler, & Gehring, 2009; Cavanagh, Frank, Klein, & Allen, 2010). Evidence for whether or not changes in post-error slowing reactivity contribute to changes in PERT could be evaluated for in ERP studies that compare the amplitude of error-related waveforms to PERT. Regardless, results from the analysis of PERT highlight the confounding factor of individual mean reaction times in the analysis of post-error slowing. Despite the fact that many researchers use PERT as the sole measure of post-error slowing in their studies, PERT alone does not capture all the relevant aspects necessary for fully understanding group
and developmental differences in post-error slowing (Shiels & Hawk Jr, 2010).
Specifically, individuals who have faster reaction times in general, as was the case for the adults in this study, will consistently show less post-error slowing based on the assessment of raw reaction times alone. When assessing for between group differences, it would be more appropriate to evaluate post-error slowing as a normalized variable where individual mean reaction times must be taken into account and controlled for (Sergeant & Van der Meere, 1988). Doing so allows for analyses to be conducted on an interindividually comparable metric, thereby providing more meaningful interpretations of between group post-error slowing. For this study, mean reaction time was controlled for in 3 ways: absolute PES, proportional PES, and z-PES.

Absolute post-error slowing (absolute PES), as calculated by the difference between PERT and mean correct RT, is another popular means of capturing post-error slowing in the error processing literature. In this study, analysis of absolute PES failed to show group differences when data was either collapsed across all blocks or examined in block 1 alone, where the majority of new learning presumably happened. However, the amount by which participants slowed down in block 1 was significantly greater than 0 for adults but not for either child groups (PERT was also significantly greater than correct RT in block 1 for adults, but not for children). These results of heightened PES in block 1 for adults but not children, conflicts with the absence of between group differences in absolute PES. One reason for the lack of significant group differences may be because taking an average measure of post-error slowing across 80 trials is too gross a measure to evaluate between group differences in post-error slowing. Inherent to the paradigm is the presence of stimuli that vary in difficulty regarding to which category it belongs.
Adjustments to the manner in which absolute PES is calculated (difference between PERT and previous trial RT, difference between PERT and cumulative/running correct RT) and controlling for the stimulus difficulty could partial out some of the variance that may be confounding the current results. As all iterations of the 80 distinct stimuli were needed to conduct the sorting strategy model analyses for this study, such manipulations to PES were not possible here. Future studies may consider comparing and contrasting different methods of calculating absolute PES values to evaluate whether group differences are actually more prevalent than were reported in this study. Despite using such a gross measure of PES, some differences in the manner in which adults and children responded to an error remain significant, with adults as a group showing absolute PES values significantly greater than 0 and children not. Such results support findings from previous studies suggesting the presence of developmental differences in PES behavior (Crone, Ridderinkhof, et al., 2004; Crone, et al., 2006; Hämmerer, et al., 2010; Van Duijvenvoorde, et al., 2008).

Measures of proportional PES (PERT/correct RT) and z-PES (PERT/SD correct RT) were also included in this study as additional measures for post-error slowing. Calculation of proportional PES was attempted as alternative means by which to control for interindividual variability in overall mean reaction times that may be confounding the results from analyses of raw post error reaction time. Controlling for interindividual differences using a proportion is useful for indexing phenomenon that display meaningful per unit changes in the confounding variable. This technique of normalizing data is frequently found in physiological studies (e.g., controlling for organ/body weight, controlling for plasma volume, etc) (see Liu, et al., 2011; Tam & Schlinger, 2007 for
Examples). Results using proportional PES as the measure of post-error slowing showed that children with ADHD and adults display significant amounts of slow down after an error in block 1, but not non-ADHD controls. That being said, there are a number of reasons as to why one may be skeptical of interpreting results obtained using proportional PES. In terms of analyzing post-error slowing, such manipulation of the data would be important if one suspected that it is the relationship between post-error slowing and mean correct reaction (i.e., that the fraction by which an individual slows down relative to his/her general reaction time) is the critical factor relevant to the utility of post-error slowing in learning. Such a supposition assumes that the speed at which an individual processes information about the stimulus and makes a decision has a linear association to the speed at which an individual processes information about an error. Furthermore, the supposition further extends that the slope of this association does not show significant intraindividual variability. These assumptions are empirical in nature but seem unlikely to hold true given evidence on the differential development of processing speed abilities across different domains of cognitive functioning (Kail & Miller, 2006). Furthermore, a review of the existing literature on post-error slowing and its neurophysiological correlates has not suggested that proportional changes in post-error slowing should exist across tasks. For these reasons, it is expected that calculating PES as a proportion of MRT may be less valid than when calculating post-error slowing as PERT or absolute PES. Given the lack of theoretical, statistical, and experimental support for the presence of an proportional relationship between overall reaction time and post-error slowing, it is not clear whether or not the results collected from the analysis of proportional PES are
representative of the actual phenomenon of post-error slowing. As a result, data from analyses using proportional PES will not be reviewed further.

Analysis of the data in terms of standard deviations (z-PES) was thought to be important for assessing whether or not the amount by which individuals slowed down after an error fell outside the range of general reaction time variability seen in a block. Results from z-PES analyses indicate that, on average, the amount by which adults, non-ADHD controls, and children with ADHD slow down after an error all fell within a standard deviation of their mean reaction times on correct trials, which is consistent with the findings from several other studies in children and adults (Chevrier & Schachar, 2010; Schachar, et al., 2004; Van De Voorde, et al., 2010). However, whether or not the post-error slowing response would be expected to fall outside the normal range of RTs for a given task, and whether or not such a finding represents something of significance for post-error slowing is unclear. As noted for proportional PES above, there is little phenomenological, experimental, or statistical evidence currently present in the literature to suggest that the degree to which an individual slows down after an error in relation to his/her overall variability is particularly pertinent to the evaluation of post-error slowing.

At the same time, increasing evidence depicting an important role of performance variability in outcome measures involving academic and social skills across the lifespan (Schmiedek, Oberauer, Wilhelm, Sub, & Wittmann, 2007) and in children with ADHD (Epstein, et al., 2010; Uebel, et al., 2010), and much more research is needed in this field of study. As a result of these complicating factors tied to the interpretation of z-PES, the remainder of this discussion will focus on those data pertaining to PERT and absolute PES.
Post-error Slowing in a Learning Paradigm

Reviewing the findings for adults, this study found that in block 1, PERT was significantly greater than CRT, absolute PES was significantly different from 0, and a significant positive relationship was observed between absolute PES and accuracy. The relationship between absolute PES and accuracy was mediated by the degree to which adults were able to establish the correct categorization structure. These block 1 relationships were absent in both groups of children, with neither child group showing PERT that was significantly greater than CRT or absolute PES that was significantly greater than 0. While non-ADHD controls showed no relationship between absolute PES and accuracy, children with ADHD showed a negative relationship between these two variables. Together, these observations from the analysis of PERT and absolute PES suggest that, in this categorization paradigm, post-error slowing follows a developmental course in its importance to learning and is impaired in children with ADHD.

Developmental course of post-error slowing. Brain regions that have been employed by adults during feedback learning show lengthy periods of development (Bunge & Zelazo, 2006; Casey, et al., 2000; Giedd, 2004). The developmental differences in the use of post-error slowing seen here matches that found in other studies measuring increasing performance monitoring efficacy. Previous cross-sectional studies using a variety of different tasks involving set-shifting (Crone, Ridderinkhof, et al., 2004), cued sorting (Van Duijvenvoorde, et al., 2008), and probabilistic reinforcement (Hämmerer, et al., 2010) have all found that the ability to use feedback to improve performance increases with age. Using behavioral data in conjunction with different types
of physiological data (e.g., heart rate, ERP), these studies determined that adults show distinct physiological changes associated with error processing that were found to be weaker or non-specific in children (Crone, Ridderinkhof, et al., 2004; Crone, et al., 2006; Eppinger, et al., 2009; Hämmerer, et al., 2010; Van Duijvenvoorde, et al., 2008). Like these other studies, findings here also show a pattern of increasing efficacy in the influence of error processing on skill acquisition.

Unlike the current study, several studies using simple reaction time paradigms such as the stop signal reaction time task (Schachar, et al., 2004), the flanker task (Van Meel, et al., 2007), and the Go/NoGo task (Van De Voorde, et al., 2010; Wiersema, et al., 2005) have found evidence of absolute PES in typically developing children. Interestingly, in this learning paradigm, neither group of children demonstrated significant PES. These findings seem to imply that PES may reflect a separate cognitive process in learning tasks than it does in speeded reaction time tasks. Perhaps the difference lies in how easily attributable the feedback information is to the source of the error. In simple reaction time tasks, there are very few options as to why an answer is wrong, and it is relatively easy for a participant to identify why an error occurred (e.g, due to a lapse in attention or a trade-off in speed versus accuracy). In contrast, the learning paradigm used in this study required the monitoring of hypotheses regarding the rules of correct categorization. Broad, over-generalized hypotheses that are typical of childhood categorization strategies are more difficult to falsify than specific, exacting hypotheses. It is possible that, given the immature principles of category formation observed in children that make this task harder for them in general, the feedback of whether their answer choice was incorrect provides little usable information for them.
As a result, the neurological processes that would typically be triggered in the service of recruiting higher levels of cognitive functioning are not elicited for employment in learning. Given this general weakness in hypothesis testing ability, children may instead resort to other means of learning that may be less efficiently applied to this task, including memorization of which stimuli belong in which category and prototype learning. Future studies may consider employing experimental designs that vary the difficulty of the hypothesis testing task, or ones that include a group of children who receive hypothesis testing training, for the purposes of determining how necessary strong hypothesis testing skills are on increasing error monitoring efficacy.

**Post-error Slowing in ADHD**

Previous findings on the types of behavioral problems frequently seen in children with ADHD (e.g., poor decision making, decreased responsiveness to future consequences, trouble incorporating feedback into their subsequent behavior), suggest the existence of disrupted error processing as a key factor in ADHD. Some theories suggest that post-error slowing is related to the status of executive functioning abilities (Botvinick, et al., 2001; Holroyd & Coles, 2002). Executive function deficits have long been associated with ADHD populations (Barkley, 1997; Willcutt, et al., 2005). Weaknesses in post-error slowing in children with ADHD could therefore be due to weaknesses in these executive control processes (Barkley, 1997). As a gross proxy for working memory differences in children with and without ADHD, the working memory subtests of the WISC-IV were administered to both groups of children. Results revealed that the sample of non-ADHD controls had a significantly higher average working
memory index as compared to their same aged ADHD peers. Contrary to what might be expected if EF drove post-error behavior modification, post-error slowing was unrelated to working memory capacity both within and between either group of children. Importantly, although the group differences in working memory were significant, averages for both children with and without ADHD fell well within the normal range of scores. As working memory has frequently been found to be impaired in ADHD populations (Willcutt, et al., 2005), it is possible that the WMI from the WISC is too gross a measure of working memory, and is not able to adequately capture the full degree to which differences exist and/or working memory is impaired in children with ADHD. As mentioned previously, the working memory measure used in this study was an index measure normed across children of the same age. Using tasks that have previously found to be able to differentiate the working memory impairments typically found in children with ADHD should be considered for future studies. Additionally, ADHD populations show highly heterogeneous symptom profiles, including differences in the type, combination, and degree to which cognitive impairments exist in any given individual with ADHD.

Based on it was originally hypothesized that children with ADHD would display a poorer relationship between post-error slowing and accuracy as compared to their same-aged typically developing peers. Several studies have previously noted volumetric and functional abnormalities in regions of the brain important for communicating observed differences in expectations and outcome to motor control areas (Botvinick, et al., 2001; Devinsky, et al., 1995; Holroyd & Coles, 2002) in children with ADHD (Krain & Castellanos, 2006; Passarotti, Sweeney, & Pavuluri, 2009; Peterson, et al., 2009; Pliszka,
Liotti, & Woldorff, 2000). Some neurophysiological studies also suggested potential
deficits in the ERP waveforms associated with error processing (Groen, et al., 2008; Van
De Voorde, et al., 2010; Van Meel, et al., 2005), further instigating the hypothesis that a
deficit in error processing may be present in ADHD, and that this deficit may be critical
to their difficulties in acquiring academic skills.

In agreement with this hypothesis, children with ADHD showed impaired ability
in the use of post-error slowing to enhance accuracy in this categorization learning
paradigm as compared to non-ADHD controls. As opposed to their typically developing
peers, who seemed to show neutral reactivity to error feedback, children with ADHD
who showed more absolute PES after an error were less accurate than those who showed
less absolute PES after an error. Although no significant differences were observed in the
average amount of post-error slowing in block 1 between the children with and without
ADHD, trend analysis examining within group variance in absolute PES reflected
significantly different patterns of responding between the two groups of children. That is,
comparing across the range of absolute PES displayed by both groups of children,
typically developing controls showed a non-significant change in accuracy whereas
children with ADHD showed decreasing accuracy. Other than post-error slowing theories
regarding higher order cognitive functions, other theorists have thought of the
phenomenon as an orienting response that simply represents arousal (Notebaert, et al.,
2009). Several researchers have incorporated difficulties with arousal regulation into the
etiological theory of ADHD (Nigg & Casey, 2005; Sergeant, 2000; Sonuga-Barke, 2002).
When post-error slowing is present in children with ADHD, their performance gets worse
rather than getting better. Although errors were not rare events, the arousing effect
brought about via the negative feedback may result in dysregulation that interferes with the ability for children with ADHD to learn. If children with ADHD do in fact have greater difficulty regulating their error feedback arousal response, methods of academic remediation may consider increasing the amount of positive reinforcement in the learning environment of a child with ADHD as well as deemphasizing errors and mistakes so as to make the learning environment may be less evocative for these children. Future studies may consider experimentally manipulating different ways of providing error feedback to determine whether or not the orienting effect of error detection can be tamped down.

**Theories of Post-error Slowing**

Error feedback processing is a proposed cognitive mechanism by which incoming information regarding an incorrect response is used to enhance performance (Ohlsson, 1996). Several cognitive etiological theories on post-error slowing are currently under debate. The three principal theories describe post-error slowing as reflections of reinforcement learning, as conflict control, or as an orienting response.

Reinforcement learning theories believe that post-error slowing is the behavioral manifestation of cognitive processes involved in comparing outcomes to expectations, where unfavorable outcomes recruit effortful, attentional control networks for the purposes of improving future performance (Holroyd, et al., 2005). In light of the consistent and significant findings regarding post-error slowing in block 1 in adults but not children, it would appear that post-error slowing does in fact reflect the recruitment of activity of such higher order cognitive processes. In the case of this particular study, individuals may have different expectations of success based on whatever working
hypotheses they are evaluating as the correct sorting strategy by which to gauge their response decisions. The hypothesis that is at the forefront of their working memory may be driving the expectations of success critical to the reinforcement theory of post-error slowing. As absolute PES was associated with accuracy and correct sorting strategy in block 1 alone in adults, such data would fit this theory of PES. Also in accordance with such a theory is the absence of an absolute PES effect on accuracy in children. In children, weak hypotheses for categorization that are not associated with strong expectations by which to compare outcome would therefore result in little observed post-error behavior modification.

These results are also consistent with conflict control theories of post-error slowing which view the phenomenon as reflective of an increased response threshold trigged by the presence of consecutive, parallel, discrepant streams of information (Botvinick, et al., 2001; Carter & van Veen, 2007). Such error processing theories posit that errors early in learning come about as a result of the presence of more than one option in action selection that could potentially lead to the goal state (Ohlsson, 1996). Accordingly, it is possible that adults have several working hypotheses active in working memory at one time, and that part of the learning process involves weakening the activation of irrelevant hypotheses and strengthening the relevant ones (Anderson, 1987; Ohlsson, 1996). These numerous possible paths to the correct answer may create parallel streams of discrepant information, leading to more post-error slowing at the start of learning (Botvinick, Cohen, & Carter, 2004; Ohlsson, 1996). Here, too, you would expect significant PES early in learning, followed by a waning effect over time as the number
and strength of irrelevant sorting strategies decreases over time, as was observed in the adult PERT and absolute PES results in the current study.

Finally, Notebaert and colleagues support an orienting account of post-error slowing that identifies the behavioral phenomenon as simply an automatic response to a rare event (Notebaert, et al., 2009). Although it is difficult to rule out the orienting response due to the fact that we could not conclude with certainty that post-error slowdown reflected the activity of higher order cognitive functioning, the orienting account of post-error slowing seems to be unlikely here as (1) adults were receiving error feedback approximately 35% of the time, which would not be considered a rare event, and (2) the fact that absolute PES was significantly related to accuracy and model use in block 1, and (3) PES did not increase as error feedback event became increasingly rare for adults in later blocks.

Both reinforcement learning and conflict control theorists see post-error slowing as a demonstration of executive processing or attentional control in the service of achieving a particular goal (Botvinick, et al., 2001; Holroyd & Coles, 2002; Rabbitt, 1966). In the case of rule-based category learning, the goal would be to acquire the correct, verbalizable, sorting strategy so as to increase task performance. The orienting account does not fit the results of this study as well as the reinforcement learning or conflict control theories given that adults still showed post-error slowdown when accuracy rates were low. To conclude, it appears that the results from this data set show stronger support for reinforcement learning or conflict control theories of PES rather than the orienting theory of PES, and that more research is needed to elucidate which one, between the two, is a more accurate description of PES in a learning paradigm.
Summary

In summary, results from this showed that, in adults, PES likely reflects higher order processing that serves to improve future performance on a learning task. It is clear that there are developmental differences in the utility of PES and error feedback in general to learning. Children, however, do not appear to be able to efficaciously incorporate PES into their skill acquisition schema. Furthermore, in contrast to the findings from adults, children with ADHD, PES may reflect dysregulation in their arousal system that results in poorer performance. The results provided here regarding adults can be explained by both reinforcement learning and cognitive control theories of PES, however an orienting response cannot be completely ruled out based on observations collected from children with ADHD. Results obtained showing increased impairment in skill acquisition with increased PES in children with ADHD supports that idea that there is a deficit in the error processing system in this group of kids, although whether this is primarily attributable to problems with initial levels of arousal or the executive control of that arousal remains unclear. Further research, including studies that more fully assess executive functioning abilities and use learning paradigms in conjunction with neurophysiological measures of error processing, are necessary to help shed light on these questions.
References


