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Exploring Executive Functions in Children with Attention Deficit Hyperactivity Disorder using Event Related Potentials

by

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ABSTRACT

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Attention deficit hyperactivity disorder (ADHD) is a prevalent neurobehavioral disorder that affects individuals in early childhood and is characterized by cognitive impairments associated with executive functioning. However, the exact nature of the impairment(s) is/are unclear. In a recent meta-analysis, Miyake, Friedman, Emerson, Witzki, Howerter, and Wager (2000) demonstrated that there are at least three separable frontal executive functions: set switching, working memory updating, and response inhibition. Here we used event-related potentials (ERPs) to investigate whether the cognitive impairments seen in ADHD are specific to one of these executive functions or rather represent a global executive functioning deficiency. The current studies examined the time course and scalp localization of executive functions in Combined Type ADHD and in comparison control children by implementing modified versions of three executive tasks used by Miyake et al. (2000), local-global, tone-monitoring, and Stroop; versions more appropriate for the ADHD population. An additional non-executive task (visual oddball) was included in order to demonstrate that the deficits in ADHD are specific to executive functioning. The goal was to determine if children with ADHD perform differently on these three executive tasks and if this difference can be attributed to a deficit associated with one or more of the executive functions. The current findings show
that ADHD impacts only a subset of cognitive operations in the executive functions, leaving the other ERPs in the executive tasks and the visual oddball unaffected.

Specifically, the ADHD group was impaired on tasks involving allocation of attention and response inhibition, the cognitive operations most closely related to the diagnostic criteria for this subtype of ADHD. These findings may extend our knowledge of the time course and localization of executive functions and provide a tool for studying the nature of disrupted executive functioning in ADHD.
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Introduction

Attention deficit hyperactivity disorder (ADHD) is a prevalent neurobehavioral disorder that affects individuals in early childhood. ADHD is characterized by three main constructs: inattention, impulsivity, and hyperactivity. Although these three constructs are multidimensional in nature, symptoms typically involve difficulty with persistence of effort or sustained attention, inhibiting behavior in response to situational demands, and excessive or developmentally inappropriate levels of activity, respectively. ADHD is divided into three subtypes based on the presence and/or interaction of these principal constructs. Predominantly Inattentive Type describes individuals who have symptoms of inattention, predominantly Hyperactive-Impulsive Type describes individuals who have symptoms of both impulsivity and hyperactivity, and individuals who have symptoms from all three constructs are termed Combined Type. The symptoms associated with these subtypes involve impairment with higher-order cognitive processing, or executive functioning. The current study describes four event-related potential (ERP) experiments conducted in children with Combined Type ADHD and in control children, to distinguish between executive and non-executive functional deficits and to test for differential impairment between different kinds of executive functioning in ADHD.

Executive Functions

So called “executive processes” play a key role in many models of cognitive functions like attention and working memory, and appear differently disrupted in some psychopathologies, like ADHD (Pennington & Ozonoff, 1996). Executive functions are conceptualized as regulatory mechanisms that control or distribute the control of various
cognitive operations. However the nature of the executive functions is often poorly defined, although their neural substrate is generally placed in the frontal cortex (Pribram, 1973; Luria, 1973). In a comprehensive review of the single cell, neuroimaging, and neuropsychological literature, Kane and Engle (2002) specifically acknowledged the critical role of the dorsolateral prefrontal cortex in executive attention and its relationship to a larger network of anterior and posterior areas associated with attention control. It has further been proposed that the prefrontal cortex may be more appropriately conceptualized as not merely a homogenous center of origin for executive operations, but rather as an adaptive, fluid resource allowing flexibility for the processing of specific cognitive operations (Duncan, 2001). This adaptive model of neural function in the prefrontal cortex is supported by extensive research showing regional specification of function within prefrontal cortex, and application of these functions to a diverse set of cognitive operations (Duncan & Owen, 2000).

**Unified or Separate Executive Functions?**

The term “executive processes” has traditionally been used as a global description of mechanisms that optimize performance in situations that require multiple cognitive processes. For example the original “central executive” in Baddeley’s (1986) model of working memory controlled and regulated two slave systems: the phonological loop and the visuospatial sketchpad. However, the central executive was not clearly defined in terms of the specific mechanisms involved. Baddeley also proposed that the “higher-level” supervisory attentional system in Norman and Shallice’s (1986) theory of attention, which distinguishes between automatic and partially automatic processes, might also be a potential model of the executive processes, but this supervisory system is
similarly under-defined. It is unclear whether these regulatory, supervisory, or executive functions represent the emergent properties of interactions between specialized and functionally distinct processing mechanisms or the operation of a single, unified central executive (Smith & Jonides, 1999).

Initial investigation into the nature of executive functions (primarily prefrontal) came from the ablation studies in monkeys, suggesting two distinct executive processes: short-term memory and behavioral inhibition, and from lesion studies in humans, suggesting a functional distinction between dorsal (cognitive) and ventral (social/emotional) paths in the prefrontal cortex. Although these lines of research occurred in parallel, inconsistencies between the non-human primate and human work hampered the development of an organized and integrated theory (Roberts, 1998). Two competing hypotheses have evolved which describe the nature of executive functions as either a single unified central executive or as separate processing mechanisms. Recent attempts to explain how the brain, specifically the prefrontal cortex, orchestrates cognitive control include parallel-distributed processing/connectionist models that support a single executive (Miller & Cohen, 2001) and empirical findings that suggest functional distinctions in the prefrontal cortex for executive control processes (Wagner, Maril, Bjork, & Schacter, 2001). A critical question that remains unanswered is whether the executive functions, be they in the frontal lobe or mediated by other neural systems, reflect aspects of a single integrated system or a collection of discrete functions.

Miyake, Friedman, Emerson, Witzki, Howarter, and Wager (2000) used confirmatory factor analysis to explore the organization and roles of executive functions, specifically the separability of three executive functions: shifting of mental sets,
monitoring and updating of working memory representations, and inhibition of preponent responses; henceforth shifting, updating, and inhibition, respectively. Miyake et al. selected shifting, updating, and inhibition because these functions are lower level processes that are easily defined operationally, there are a variety of simple yet robust tasks that tap them, and they are thought to underlie the more complex tasks traditionally used to evaluate executive processing.

Miyake et al. (2000) selected three tasks each to assess the three proposed executive functions: for shifting were the plus-minus, number-letter, and local-global tasks; for updating the keep track, tone-monitoring, and letter memory tasks; for inhibition the anti-saccade, stop-signal, and Stroop tasks. For each of the executive functions, tasks were chosen that varied in the operations used to engage each particular function. For example, the tasks selected to measure shifting employed a variety of different stimuli including numbers, letters, and shapes. The commonality among these tasks was therefore the shifting cognitive operation and not other inherent task requirements unrelated to executive functioning. Furthermore, implementing a diverse set of tasks for the executive process reduced the possibility of viable alternative explanations of the results.

Confirmatory factor analysis showed that the three executive functions were separable, though moderately correlated. Several models were evaluated to determine the extent to which the variance in the three constructs could be accounted for. The three-factor model suggesting that the three executive functions were distinguishable yet related constructs (i.e. three unique constructs with some shared variance) fit the data better than alternative models.
The Miyake et al. (2000) study is one conception of the organization of executive functions that argues for the separability of three executive functions. A study by Sylvester, Wager, Lacey, Hernandez, Nichols, Smith, and Jonides (2003) used functional magnetic resonance imaging (fMRI) to evaluate the separability of two executive functions: shifting (switching attention between tasks) and inhibition (resolution of interference between competing task responses). In the first experiment, a counter-switching task was used in which subjects silently rehearsed the number of left or right pointing arrows presented in several blocks. Shifting was evaluated within each block, whereas inhibition was evaluated between blocks. Trials in which successive arrows pointed the same direction were “non-switch” trials and trials in which successive arrows pointed in the opposite direction were “switch” trials that required a switch in the counter (left or right) to be updated. A stimulus-response compatibility task was used to measure inhibition in which a screen indicating “SAME” or “OPPOSITE” preceded each block and informed subjects whether or not their motor response would be compatible or incompatible with the direction of the arrows. On SAME blocks subjects would use their left finger to respond to a left-pointing arrow and their right finger for a right-pointing arrow. On OPPOSITE blocks subjects would use their left finger to respond to right-pointing arrows and their right finger for left-pointing arrows.

Behavioral results indicated that subjects were faster at responding on non-switch than switch trials and on compatible compared to incompatible trials. Imaging results showed considerable overlap between the two tasks, particularly in the bilateral dorsolateral premotor and parietal areas and possibly in the medial frontal cortex, inferior frontal gyrus, and extrastriate cortex. The authors suggested that the overlap in the
parietal and premotor areas (close to the parietal eye fields and frontal eye fields) may be attributed to eye movements in response to the presentation of the arrows (differentially affecting experimental and control conditions) and therefore conducted a second experiment in order to control for this possibility.

In the second experiment shifting and inhibition were evaluated independently of one another and a saccade-control task was added. The same tasks used in the first experiment were used in the second experiment, although administered separately, with minor modifications to the counter-switching task. In the revised counter-switching task, subjects were asked to respond to each arrow with both left and right fingers instead of responding to the compatibility or incompatibility of the arrows. The authors also manipulated the percentage of switch trials within two types of blocks: “high-switch” and “low-switch.” In the high-switch block an average of 70% of the trials were switch trials and in the low-switch block an average of 20% of the trials were switch trials. The additional saccade-control task required subjects to direct their gaze toward a fixation cross at one of eight randomly selected locations on the screen.

Behavioral results in the counter-switch task again showed subjects were faster at responding on non-switch than switch trials and had faster response times in the low-switch as compared to high-switch blocks, indicating engagement of the switch operation by the task. In the stimulus-response compatibility task subjects were also again faster in the compatible versus incompatible blocks. In the imaging analysis, all voxels activated during the saccade-control task were excluded from further analyses to eliminate eye movements as a possible confound. A region-of-interest (ROI) analysis confirmed substantial overlap of activations in the bilateral superior parietal cortex, left dorsolateral
prefrontal cortex, and medial frontal cortex for the two experiments. Paired t-tests indicated some areas were preferentially activated in one of the two tasks. There was greater activation in bilateral extrastriate cortex and left posterior superior parietal cortex in the counter-switching task and greater activation in right parietal cortex, premotor cortex, frontopolar cortex, and bilateral caudate/putamen in the stimulus-response compatibility task. These results were interpreted as showing that executive processes have both a common cognitive mechanism involved with the allocation of attention, shown by activation in the superior parietal cortex, and separate mechanisms that are unique to switching attention and inhibition of competing responses, indicated by activation in a posterior region of the superior parietal cortex and frontopolar cortex respectively.

One potential problem with the Sylvester et al. (2003) study is that the counter-switching task was a more complex task than the inhibition task in that multiple executive processes were required. In the counter-switching task, subjects not only had to switch from counting one arrow to the other but also had to perform the counting operation itself for both left and right-pointing arrows. Therefore this task was not purely a task requiring attention switching but also involved monitoring and updating of information. Miyake et al. (2000) showed these two executive processes (i.e. shifting and updating) to be somewhat related but functionally distinct.

ERP and fMRI Correlates of Three Executive Functions

Other hemodynamic imaging and ERP studies have examined the switch, update, and inhibit executive functions.
Shifting. In a study by Moulden, Picton, Meiran, Stuss, Riera, and Valdes-Sosa (1998), subjects had to decide whether a target was in the upper or lower visual fields, or whether it was in the right or left visual fields; the task on the current trial indicated by a cue. The occipital N200, parietal P390, and frontocentral N430 to the cue were all larger when that cue signaled a task switch (upper/lower to left/right or visa versa), suggesting that both frontal and posterior cortices are involved in set switching. Swainson, Cunnington, Jackson, Rorden, Peters, Morris, and Jackson (2003) conducted separate experiments with ERP and fMRI using a go/wait paradigm in which subjects responded to left or right arrows at stimulus onset (GO task-green arrows) or stimulus offset (WAIT task-red arrows). Consistent with the electrophysiological results obtained by Moulden et al., there was greater N200 amplification obtained when switching from the Go to the WAIT task, but the N200 was located over the frontal region instead of the occipital region. fMRI activations associated with task switching were located in the right ventrolateral prefrontal cortex. Since these two effects occurred only in switches to the WAIT task, the authors concluded that the effects indexed a switch into a response-suppression mode instead of withholding an immediate response or the actual switching between tasks. Thus the apparent inconsistencies between the ERP findings in these two studies might be explained in the different tasks utilized and the differential engagement of task switching versus switching plus inhibition (see discussion of the no-go N200 below).

Updating. Kiss, Pisio, Francois, and Schopflocher (1998) recorded visual ERPs in a series of experiments while participants performed memory updating tasks. In these tasks a series of single numbers were presented followed by a pair (Experiments 1 and 2)
or set of three numbers (Experiment 3) that were either the same as (target) or different from (non-target) the two or three single stimuli that immediately preceded the pair or triplet. Subjects were to respond to all single stimuli and paired non-targets with the left button and targets with the right button (Experiments 1 and 2) or respond with the middle button for single stimuli, the right button for targets, and the left button for non-targets (Experiment 3). The centroparietal P300 was larger in the memory tasks than in the control task, consistent with Donchin's (1981) context updating hypothesis which proposed that the P300 is elicited during tasks that require updating the contents of working memory.

Inhibition. A study on the time course of the Stroop interference effect by Liotti, Woldorff, Perez, and Mayberg (2000) showed a broad medial dorsal negativity between 350-500 ms, with the estimated generators in the anterior cingulate, in the conflict compared to the congruent condition. A later prolonged positivity between 500-800 ms to the incongruent stimuli was present over the left superior temporoparietal scalp. Using an auditory discrimination task Kiefer, Marzinzik, Weisbod, Scherg, and Spitzer (1998) found an early (around 260 ms post stimulus) negative effect (N200) of response inhibition over the inferior prefrontal areas and a later (between 300-600 ms post stimulus) positive (P300) affect over the left lateralized frontocentral region. Similarly, Jackson, Jackson, and Roberts (1999) used a visual go/no-go task and reported a no-go N200 over the frontal cortex followed by a P300 over the posterior parietal region. Slight discrepancies in the inhibition findings could be attributed to the task and stimulus materials utilized.
In summary, the above findings show effects during task switching in both frontal and posterior regions, effects during memory updating in the parietal region, and a pattern of early negativity followed by later positivity during response inhibition in frontal and parietal regions. To our knowledge, only one neuroimaging (Sylvester et al., 2003) and no electrophysiological studies have examined more than one of the three executive functions, switching, updating, and inhibition, in the same participants. We recently conducted a study that explored the time course and scalp location of ERP effects due to set shifting, working memory updating, and response inhibition using local-global, tone-monitoring, and Stroop tasks, respectively (Kothmann & Potts, in preparation).

The study was conducted to identify ERP components associated with the three executive processes described by Miyake et al. (2000) and to describe the specific cognitive operations indexed by those ERP components. Participants performed three separate tasks, designed to tap one of the aforementioned executive functions and known to produce reliable ERP effects. A local-global task was used to engage set/task shifting, a tone-monitoring task was used to engage working memory updating, and a Stroop task was used to engage behavioral inhibition. Results from these experiments indicated several component cognitive operations, with distinct temporal course and neural substrates, which differentially contribute to these executive functions. These ERP findings were consistent with previous studies independently investigating the executive functions and provide a foundation on which to explore the nature of disrupted executive functioning in ADHD (refer to Table 1 for a summary of the ERP components and the cognitive mechanisms indexed for each of the three tasks).
Table Legend

Table 1. Summary of significant ERP findings and cognitive operations (CO) from Kothmann & Potts (in preparation) for the two central (C-N2 and C-P6) and three parietal (P-P2, P-P3, and P-N4) components in the local-global, tone-monitoring, and Stroop tasks. Significance levels denoted as follows: * = < .05, ** = < .01, *** = < .001.

<table>
<thead>
<tr>
<th></th>
<th>Local-global</th>
<th>Tone-monitoring</th>
<th>Stroop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Switch (S) &gt; No Switch (NS) *</td>
<td>Control (C) &gt; Memory Update (MU) *</td>
<td>LH &gt; RH *</td>
</tr>
<tr>
<td>C-N2</td>
<td>Left Hemisphere (LH) &gt; Right Hemisphere (RH) ***</td>
<td>No Response (NR) &gt; Response (R) ***</td>
<td></td>
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<tr>
<td>200-270 ms</td>
<td>CO = Stimulus-response mapping inhibition</td>
<td>NR &gt; R in RH *</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>CO = Response inhibition (classic no-go)</td>
<td></td>
</tr>
<tr>
<td>C-P6</td>
<td>S &gt; NS **</td>
<td>MU &gt; C *</td>
<td>Incongruent &gt; Neutral *</td>
</tr>
<tr>
<td>550-750 ms</td>
<td>LH &gt; RH ***</td>
<td>RH &gt; LH **</td>
<td>CO = Post-response evaluation</td>
</tr>
<tr>
<td></td>
<td>S &gt; NS in LH *</td>
<td>MU &gt; C in NR *</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO = Post-response evaluation/stimulus response mapping reconfiguration</td>
<td>NR &gt; R in RH ***</td>
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<tr>
<td></td>
<td></td>
<td>CO = Post-response evaluation</td>
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<tr>
<td>P-P2</td>
<td></td>
<td>R &gt; NR ***</td>
<td></td>
</tr>
<tr>
<td>200-260 ms</td>
<td>CO = Response inhibition</td>
<td></td>
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<tr>
<td>P-P3</td>
<td></td>
<td>R &gt; NR ***</td>
<td></td>
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<tr>
<td>300-400 ms</td>
<td>CO = Relevance effect</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>LH &gt; RH *</td>
<td>MU &gt; C *</td>
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</tr>
<tr>
<td>P-N4</td>
<td></td>
<td>NR &gt; R ***</td>
<td></td>
</tr>
<tr>
<td>400-540 ms</td>
<td>CO = Task difficulty</td>
<td></td>
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ERP Indices of Cognitive Operations

Parietal Positivity. The P3 (or P300) was defined using the oddball task, which contains frequent, usually task-irrelevant stimuli and rare, usually task-relevant stimuli, with many minor modifications, like inclusion of single-presentation task-irrelevant items ("novels"). In the most common version, the auditory oddball, there is a large, central-parietal positivity, peaking at about 300 ms post-stimulus, that is larger to the rare stimuli when they are task-relevant. Based on this pattern of results, it was hypothesized that the P3 indexed the orienting of attention to rare items and/or direction of attention to task-relevant items and/or context updating, the updating of the contents of working memory when a rare, relevant event occurs (Donchin & Coles, 1988; Johnson, 1988; Verleger, 1988). Subsequent research has demonstrated that there is more than one kind of P3, and that the P3 is comprised of multiple subcomponents. For example, modifications of the oddball to separate rarity from relevance processing have revealed an earlier, more anterior P3a, associated with rarity, and a later, more posterior P3b, associated with relevance processing (Courchesne, Hillyard, & Galambos, 1975). A visual form of the oddball produces a P3 that is later and has a more anterior distribution that the auditory oddball, but since it responds to cognitive manipulations in the same manner as the auditory, it is generally assumed to reflect the same underlying cognitive processes.

More recently, any number of experiments not including rarity or task-relevance as explicit factors (e.g. language or working memory tasks), have elicited "P3-like" components (i.e. positivities over superior, posterior scalp sites, with latencies ranging from roughly 300-600 ms), and it remains an open question what the specific cognitive operation(s) are indexed by the P3 and what the exact neural generators of the P3 are.
Some authors have attempted to address (or avoid) the issue by employing alternative terms for P3-like ERP components, like using specific latencies (e.g. P350-450) or somewhat generic terms, like "late positive complex" (LPC). The term LPC has been used to describe a variety of effects including repetition priming, episodic memory retrieval, and task switching (Rugg, 1990; VanPetten, Kutas, Kluender, Mitchiner, & McIsaac, 1991; Jackson, Swainson, Cunnington, & Jackson, 2001).

**Frontal Negativity.** There is a well-described frontocentral N2 between approximately 250-350 ms that is larger on trials in which a response is withheld (no-go) compared to trials on which a response is executed (go) (Bokura, Yamaguchi, & Kobayashi, 2001; Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003; Pfefferbaum, Ford, Weller, & Kopell, 1985). There is debate as to whether this no-go N2 represents the inhibition of a motor program (Kopp, Mattler, Goertz, & Rist, 1996) or mediation among conflicting response options (Nieuwenhuis et al., 2003), as well as whether it is a general inhibitory mechanism or specific to some stimulus modalities or response options (Falkenstein, Koshlykova, Kiroj, Hoormann, & Hohnsbein, 1995; Nieuwenhuis, Yeung, & Cohen, 2004).

An additional debate in the literature concerns the relationship between the N2 and N4. The N4, first described by Kutas and Hillyard (1980a), is a negative deflection (peaking around 400 ms) over central parietal scalp that is larger to semantically inappropriate (incongruent) than appropriate (congruent) final words of a sentence and interpreted as reflecting the semantic expectancy for a word. Polich (1985) claimed that the N4 is a latency-shifted or delayed N2 which is sensitive to violations of expectancy, however it has been disputed whether or not the distributions of the N4 and N2 are
sufficiently similar to regard them as the same component. Deacon, Breton, Ritter, and Vaughan (1991) found no significant differences in topography for the N2 and N4 components, whereas Connolly, Stewart, and Phillips (1990) found differences in topography as well as that the two effects co-occurred. It remains unclear whether the frontal negativity indeed represents orthogonal effects, although the N2 and N4 are generally assumed to represent separate components. The onset of the frontal negativity varies greatly between tasks, and coincidentally so do the names associated with the component (i.e., N2, N4).

Disrupted Executive Processing in ADHD

Extensive behavioral research has shown general impairments on a variety of executive function tasks in ADHD (see Pennington & Ozonoff, 1996 for a complete review; Shallice, Marzocchi, Coser, Del Savio, Meuter, & Rumiati, 2002). Pennington & Ozonoff (1996) reviewed eighteen studies investigating executive functions in ADHD and control groups with fifteen of the studies showing significant group differences in one or more of the executive measures assessed (60 executive function measures assessed across studies with 40 or 67% showing significantly worse performance and none significantly better in the ADHD groups). The Wisconsin card-sorting task (WCST), a complex task used to assess attention set shifting, showed impaired performance in the ADHD group in only four of the ten studies included in the meta-analysis. However, consistent group differences were found on working memory (sequential memory task and self-ordered pointing task) and inhibition tasks (Stroop, go/no-go, and anti-saccade), with significantly poorer performance in the ADHD participants. The performance deficit for the ADHD groups showed specificity to executive tasks, with significantly
fewer of the non-executive tasks showing group effects (54 non-executive tasks measured with only 19 or 35% showing group differences).

Although the behavioral literature does not consistently show differences in all measures of executive functions (e.g. switch), it suggests a general impairment for children with ADHD on many measures of executive function and few measures of non-executive functions. An inherent limitation to these behavioral studies is that only the final product of cognition, the response, can be measured. ERP studies enable measurement of brain activity before a response is produced and more fully index the individual cognitive processes involved in a particular task. However, few ERP studies on executive functioning in ADHD children have been conducted.

Most of these ERP studies have investigated response inhibition and employed paradigms such as the go/no-go task (Overtoom, Verbaten, Kemner, Kenemans, van Engeland, Buitelaar, Camfferman, & Koeleoga, 1998) and stop signal task (Pliszka, Liotti, & Woldorff, 2000; Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005). Findings generally show reduced amplitude in components for ADHD as compared to control children. Consistent with the evidence implicating the role of the prefrontal cortex in executive functioning, fMRI findings have shown subnormal activation of the prefrontal systems during the stop task (Katya, Overmeyer, Taylor, Brammer, Williams, Simmons, & Bullmore, 1999). To our knowledge, no electrophysiological studies have explicitly investigated attention set shifting or updating of working memory in the ADHD population (although the stop signal task requires some attention shifting). Thus, although set shifting and updating have received minimal empirical evaluation in ADHD children to date, these tasks have the potential to help identify whether children with
ADHD have a general executive impairment or specific deficits associated with particular executive functions.

The current study describes ERP components related to set shifting, working memory updating, and response inhibition using versions of the local-global, tone-monitoring, and Stroop tasks, adapted from Miyake et al. (2000) in Combined Type ADHD and age-matched controls. The purpose of this study is to augment our understanding of executive function deficits in ADHD by using ERPs to explore the time course and localization of these executive processes. This research seeks to determine if the cognitive deficits displayed by ADHD children represent a global executive deficit or are specific to particular executive processes, a distinction that may ultimately impact treatment decisions.

In addition to the executive tasks, a non-executive task was included to determine if the cognitive deficits in ADHD are specific to executive functioning by eliminating a non-specific neural dysfunction hypothesis of ADHD. Since the ERP/ADHD literature is small and not entirely consistent, we were unable to find a non-trivial task in which ADHD children unequivocally perform on the same level as controls. However, the oddball task is a ubiquitous, non-executive ERP task, and has the largest literature in both normal and various patient populations for comparison purposes (Donchin & Coles, 1988; Verleger, 1988; Polich & Herbst, 2000).

Using the visual oddball task as a non-executive function task is appropriate for several reasons. The nature of the task is to respond to a task relevant, infrequent stimuli (targets) embedded in a stream of frequent stimuli (standards). The task is consistent (always respond to targets, never to standards) and thus involves minimal executive
components (updating, switching, etc.). Targets produce a large amplitude ERP component, the P300 or P300b, with a topographical distribution over posterior scalp regions (Sutton, Braren, Zubin, & John, 1965). The oddball is a very simple task that has been used in many studies of patients with psychiatric disorders (such as depression and schizophrenia). Such studies show similar reaction times and P300 amplitudes, i.e. the visual P300b is not always reduced in schizophrenics compared to controls (Ford, 1999).

To our knowledge the visual oddball has not been examined in the ADHD population and behavioral studies have shown mixed results on sustained attention/vigilance tasks in ADHD children (Pennington & Ozonoff, 1996). We have chosen to use a visual oddball task that includes novel stimuli, first described by Courchesne et al. (1975), to evaluate the possibility that ADHD children may show greater response to the novel, task irrelevant stimuli than controls because of increased distractibility.

Hypotheses

Based on the electrophysiological results reported by Kothmann and Potts (in preparation) and previous ERP studies on ADHD, we have some idea of the ERP components and associated cognitive operations that represent these executive functions. However, the current study is the first to evaluate multiple executive functions in the same ADHD sample using the ERP methodology. If there are general cognitive deficits spanning executive and non-executive functions in ADHD, then there should be ERP reductions in all three executive function tests as well as in the visual oddball task. If cognitive deficits in ADHD are confined to executive functions, and impact all executive functions, then there should be ERP reductions in all three executive function tasks but not in the non-executive visual oddball task. If ADHD impacts only a subset of executive
functions, e.g. inhibition only, then the ERP reductions should be confined to the test of that function, i.e. the Stroop task or to tasks that include that cognitive operation as a subcomponent, leaving the ERPs in the other executive tasks and the visual oddball unaffected.

**Component Terminology**

*Parietal Positivity*

In the current manuscript, we use the term "P3b" to refer to the parietal positivity elicited in the visual oddball (we employed a visual oddball since two of the three executive tasks employed visual stimuli, and thus the visual oddball provides a better non-executive control task), and follow the convention of interpreting this component as indexing a lower-level orienting of attention to rare, task-relevant stimuli (Sutton et al., 1965). We use the term "LPC" to refer to the later parietal positivity elicited in the local-global and Stroop tasks, and interpret it as indexing executive function related cognitive operations, as defined by the tasks (see the specific and general discussions that follow). Finally, we use the term "P3" to describe the posterior positivity elicited in the tone-monitoring task and relate it to the classic updating P3 described by Donchin and Coles (1988) in a series of experiments studying working memory function.

*Frontal Negativity*

Here we use the term "N4" to refer to the frontal negativity in the local-global task, and interpret it as indexing task switching consistent with the frontocentral N430 reported by Moulden et al. (1998) and frontal N2 (360-400 ms) reported by Swainson et al. (2003). We use the term "N3" to refer to the earlier frontal negativity elicited in the tone-monitoring task, and relate it to the well-described frontocentral N2 that is larger on
trials in which a response is withheld (no-go) compared to trials on which a response is executed (go) (Bokura et al., 2001; Kopp et al., 1996). Finally, we use the term "N4" to describe the frontal negativity elicited in the Stroop task and relate it to the early negativities (350-500 ms and 230-320 ms, respectively) described by Liotti et al. (2000) using a Stroop task and Kiefer et al. (1998) using a go/no-go paradigm to evaluate response inhibition.

**Research Design and Method**

**Participants**

Twenty (10 ADHD and 10 control) children participated in the study. Participants had normal or corrected to normal vision and hearing. All participants completed each of the three executive function paradigms and non-executive task (within subjects design). To minimize issues of a heterogeneous ADHD sample, the current study used a patient population consisting of Combined Type subjects only. While the theoretic basis of this study does not distinguish between different subtypes of ADHD, Combined Type ADHD involves symptoms for all three principal constructs: inattention, impulsivity, and hyperactivity and thus is a reasonable subpopulation on which to conduct initial analyses.

**Combined Type ADHD Subjects.**

ADHD subjects (M = 12.1 years old, 6 males) were referred by Dr. Steve Pliszka, chief of the Division of Child and Adolescent Psychiatry, Department of Psychiatry at the University of Texas Health Science Center, San Antonio (UTHSCSA) or obtained using a flyer posted on the UTHSCSA main campus. All ADHD subjects were identified through medical records to show a diagnosis of ADHD. In addition, the subject's parents
completed diagnostic assessments including the Diagnostic Interview Schedule for Children-Parent Version (DISC) (Shaffer, Fischer, Dulcan, Davies, Piacentini, Schwab-Stone, Lahey, Bourdon, Jensen, Bird, Canino, & Regier, 1996) and the Iowa Conners Teacher Rating Scale (CTRS) used to identify children as Combined Type (Inattention/Overactivity factor). The ADHD subjects were required to have a baseline score of at least 1.5 standard deviations (SD) above the mean for their age on the CTRS Inattention/Overactivity factor. Exclusionary criteria were the presence of any co-morbid anxiety, depressive, conduct, or psychotic disorder identified during the diagnostic procedures (DISC). All of the ADHD subjects were positive responders to stimulant treatment and were undergoing stimulant treatment for at least one year, but were kept off medication for a minimum of twenty-four hours prior to testing.

In addition to the diagnostic assessments, subjects completed a thirty-minute intake assessment consisting of two achievement measures in order to control for intelligence quotient (IQ) and reading abilities. Subjects completed the Kaufman Brief Intelligence Test (KBIT) and the reading recognition subtest of the Peabody Individual Achievement Test-Revised (PIAT-R). Results from the IQ tests were verified by Dr. Jim Stedman, a licensed psychologist. Subjects were fully literate in English, attended regular schools, and did not require any special education or tutoring for educational deficiencies.

Control Subjects

Control subjects (M = 11.9 years old, 6 males) were recruited from the San Antonio community using flyers. Responders (parents) were telephone screened to meet initial criteria of the absence of ADHD and a history of psychiatric or neurological
diagnoses in their children. Eligible parents completed the DISC and CTRS to confirm their children did NOT meet the criteria for ADHD or any other psychiatric disorder included in the DISC evaluation, and had a baseline score of no more than 1 standard deviation above the mean for their age on the CTRS. Control children completed the two IQ tests and were also fully literate in English, attended regular schools, and did not require any special education or tutoring for educational deficiencies. Control subjects were chosen so that they were not significantly different from the ADHD group on age, education level, or sex.

The diagnostic assessment and achievement data for the two groups were analyzed using between groups t-tests. The ADHD group (M = 81, SD = 7) scored higher on the CTRS than the control group (M = 47, SD = 6), t (18) = 11.65, p < .0001. All ADHD and no control children had a score of 65 or greater indicating a positive Combined Type ADHD diagnosis. There was no difference between the ADHD (M =104, SD = 11) and control group (M = 110, SD = 12) on the KBIT; p = .3 or between the ADHD (M =102, SD = 16) and control group (M = 110, SD = 8) on the PIAT-R; p = .19. The null results obtained for the achievement data confirm that the two groups did not differ for IQ and reading abilities (refer to Table 2 for a summary of demographic, diagnostic assessment, and achievement data for the two groups).

**EEG Data Acquisition and Signal Processing**

At the beginning of each session, subjects were introduced to the EEG recording procedures by a trained research assistant. All EEG data were acquired using a customized cap with an array of 64 equally spaced electrodes (Electrocap Inc., Eaton, OH). Six additional electrodes were applied directly on the skin around the eyes and the
Table Legend

Table 2. Summary of demographic, diagnostic assessment, and achievement data for ADHD and control subjects.

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Control

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cheeks and behind the ears (two at the external canthi, two infraorbital, and one each at the left and right mastoid) to record eye movements. In order to improve the electrode contact, the skin was lightly cleaned with rubbing alcohol and the electrodes were filled with electrogel (made of water and salt). The scalp was lightly scraped using a disposable wooden stick to improve contact between the electrode and scalp. Application of all 64 channels took approximately one hour.

EEG data were acquired continuously sampled at 400 Hz., bandpass .01 - 100 Hz. analog filtering, gain of $10^4$, impedances $<5\, \text{k}_\Omega$, referenced to the right mastoid (left mastoid active external electrode), and segmented off-line into 1000 ms epochs spanning 200 ms pre-stimulus to 800 ms post-stimulus. Data were digitally screened for artifact (eye blinks or movements, subject movement, or transient electronic artifact) and contaminated trials removed off-line. Remaining data were sorted by condition and averaged to create the ERPs. Averaged ERP data were digitally filtered at 20 Hz lowpass to remove residual high-frequency noise, baseline corrected over the 200 ms prestimulus period, and rereferenced into an average reference frame to remove topographic bias due to choice of reference site (Dien, 1998). Finally the subject-averaged ERPs were averaged together to produce the mean waveform across subjects, the grand average waveform. In order to examine group differences in the selected effects at specific scalp sites, including possible differences in scalp topography, mean voltage amplitudes in the latency windows for all components for each subject underwent a normalization procedure with the square root of the mean of squares method (McCarthy & Wood, 1985). Statistical analyses were performed on the normalized subject-averaged ERPs
with the normalized subject averages being the observations. The waveform plots were performed on the grand average data.

**Stimulus Presentation and Behavioral Response Collection**

Stimulus presentation and behavioral response collection was controlled by a Dell computer (Dell Computer, Austin) running e-prime software (Psychology Software Tools, Pittsburgh). Auditory stimuli were presented through Sony headphones. Manual responses were collected with a 4-key game-pad.

Subjects were seated in a reclining chair placed so that subject's eyes are 40 cm from the center of the computer screen. Subjects were instructed to remain as still as possible with their eyes on the fixation mark throughout the block and requested to refrain from blinking as much as possible while the stimuli were appearing. Breaks were provided every 3-4 minutes so that subjects could rest their eyes.

**Stimuli and Timing**

For each of the following tasks, subjects received explicit instructions on how to perform each task and a practice session to familiarize them with each task prior to experimental trials. The practice session was repeated when necessary.

**Local-Global Task (Task Switch)**

Visual stimuli were large letters composed of smaller letters. The experimental stimuli were either large “As” composed of small “Bs” or large “Bs” composed of small “As”. The modifications to the original task were so that the stimuli (“As” made of “Bs” and vice versa) and the response (“A” or “B”) were identical and therefore could possibly cause interference. To address this possibility alternating blocks of neutral stimuli (“As” or “Bs” made of “Xs” or “Xs” made of “As” or “Bs”) were also included for comparison.
Stimuli were presented in either red or yellow font. When stimuli were presented in yellow font, subjects were instructed to respond to the large (global) letter and press the corresponding keypress (A or B). When stimuli were presented in red font, subjects were instructed to respond to the small (local) letter and press the corresponding keypress. Font color for visual stimuli and response hand (whether A or B is on the left or right) were counterbalanced across subjects. Subjects performed 6 total blocks (alternating between experimental and neutral stimuli) of 80 trials with a break after each block. A "switch" was defined as the presentation of a stimulus in yellow font followed by a stimulus in red font or vice versa. A "non-switch" was defined as the presentation of consecutive stimuli in red or yellow font. At the beginning of each trial there was a fixation cross at the center of the screen for 250 ms. The visual stimuli replaced the fixation mark, remained onscreen for 500 ms, and were followed by a fixation cross presented for a random inter-stimulus interval (ISI) between 1500 and 2000 ms. Stimuli were chosen pseudorandomly so that no more than four "non-switches" and three "switches" would occur in sequence. Half the stimuli were "switches" and half were "non-switches".

Tone-Monitoring Task (Memory Update)

Auditory stimuli were 220 Hz. (low) and 880 Hz. (high) pitched tones. A series of randomly presented tones of each tone type were presented. At the beginning of each trial there was a fixation cross at the center of the screen for 250 ms followed by the presentation of the tone for 100 ms and a random ISI between 1500 and 2000 ms (the fixation cross was unchanged during auditory presentation and remained on the screen during the entire trial). Subjects performed two different tasks in 5 blocks of 48 trials.
each (total 10 blocks) with a break after each block. In the experimental condition subjects were instructed to respond to the second presentation of the low and high tone by pressing a corresponding keypress ("low" or "high") which required subjects to monitor and keep track (update) of the number of times each tone type was presented. After a response was made subjects were instructed to respond to the next second tone presentation for each tone type. In the control condition, subjects were instructed to respond to the absolute second presentation of a tone and press the corresponding keypress ("low" or "high"). This required subjects to monitor the tones presented and respond to every other tone, but not to update any information. Subjects performed alternating blocks of the experimental and control conditions. Response hand (whether "low" or "high" was on the left or right) was counterbalanced across subjects.

Stroop Task (Inhibition)

Visual stimuli were color words. The words "RED", "YELLOW", "GREEN", AND "BLUE" were presented in the font colors red, yellow, green, and blue. All possible combinations were included. Subjects were instructed to name the font color in which the stimulus was presented in by pressing a corresponding keypress (buttons were red, yellow, green, or blue and counterbalanced across subjects). A congruent trial was one in which the color word and font color were the same. An incongruent trial was one in which the color word and font color were different. Each of the two trial types was equiprobable. At the beginning of each trial there was a fixation cross at the center of the screen for 250 ms followed by the presentation of the visual stimulus for 150 ms and a fixation cross presented for a random ISI between 1500 and 2000 ms. Subjects performed 4 blocks of 96 trials with a break after each block.
**Visual Oddball Task (Non-executive Control)**

Visual stimuli were “Ts”, “Xs”, and letter stimuli from the imaginary fonts DS_Kha'zuldum, Naboo_Futhork, and newAurabesh (these stimuli were unidentifiable symbols that did not resemble standard English fonts). “Ts” or “Xs” were identified as either targets (20%) or standards (70%) and counterbalanced across subjects. Novel stimuli (imaginary fonts stimuli) were included to assess more phasic aspects of attention (10%). Subjects were instructed to respond to targets by pressing a corresponding keypress (button was labeled either “T” or “X”) and withhold a response to all other stimuli (standard and novel stimuli). Targets, standards, and novel stimuli were randomly presented within each block. At the beginning of each trial there was a fixation cross at the center of the screen for 250 ms followed by the presentation of the visual stimulus for 150 ms and a fixation cross presented for a random ISI between 1500 and 2000 ms. Subjects performed 4 blocks of 100 trials with a break after each block.

**Results**

Behavioral analyses, reaction time (RT) and error, were conducted for each of the four tasks (see Tables 3 and 4 for a summary, respectively). Dependent measures for the electrophysiological analyses were the mean voltage amplitude within temporal windows across frontal and parietal region-of-interest (ROI) channel groupings, chosen based on prior ERP studies of executive functions that found effects at frontocentral and parietal sites (see Figure 1a-d for an approximation of electrode location based on the standard 10-20 location; the exact electrodes included in each ROI are listed below with a, p, s, and i indicating anterior, posterior, superior, and inferior to 10-20 location, respectively). A total of four ROIs were selected for analysis, two each over frontal and parietal sites.
Table Legend

Table 3. Summary of the RT data in the oddball, local-global, tone-monitoring, and Stroop tasks for ADHD and control subjects.

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<th>LG-NNS</th>
<th>LG-NS</th>
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Control

| 1    | 642  | 817    | 1131  | 720    | 826   | 721   | 575  | 651 | 740 |
| 2    | 540  | 810    | 1027  | 663    | 719   | 743   | 653  | 816 | 888 |
| 3    | 565  | 741    | 770   | 626    | 658   | 749   | 727  | 803 | 960 |
| 4    | 630  | 1204   | 1205  | 1054   | 1060  | 841   | 837  | 763 | 877 |
| 5    | 585  | 1059   | 1073  | 806    | 834   | 576   | 520  | 786 | 927 |
| 6    | 725  | 774    | 882   | 673    | 723   | 764   | 727  | 717 | 738 |
| 7    | 589  | 807    | 995   | 649    | 695   | 575   | 554  | 706 | 794 |
| 8    | 674  | 1073   | 1110  | 902    | 920   | 673   | 702  | 793 | 839 |
| 9    | 851  | 972    | 1072  | 984    | 1034  | 827   | 823  | 1012 |1026|
| 10   | 537  | 859    | 952   | 632    | 652   | 624   | 540  | 658 | 675 |
| Mean | 634  | 912    | 1022  | 771    | 812   | 709   | 666  | 771 | 837 |
| SD   | 97   | 156    | 128   | 157    | 150   | 95    | 116  | 103 | 111 |

OB-T = oddball targets  
LG-CNS = local-global conflict no switch  
LG-CS = local-global conflict switch  
LG-NNS = local-global neutral no switch  
LG-NS = local-global neutral switch  
TM-MU = tone-monitoring memory update  
TM-C = tone-monitoring control  
S-C = Stroop congruent  
S-I = Stroop incongruent
Table Legend

Table 4. Summary of the error data in the oddball, local-global, tone-monitoring, and Stroop tasks for ADHD and control subjects.

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Control

| 1    | 0    | 23     | 48    | 2      | 4     | 14    | 10   | 8   | 21  |
| 2    | 0    | 9      | 23    | 2      | 0     | 7     | 7    | 13  | 23  |
| 3    | 1    | 50     | 60    | 16     | 28    | 0     | 3    | 17  | 38  |
| 4    | 0    | 36     | 32    | 6      | 5     | 27    | 0    | 0   | 0   |
| 5    | 0    | 29     | 28    | 9      | 12    | 6     | 2    | 10  | 17  |
| 6    | 0    | 18     | 55    | 7      | 16    | 8     | 4    | 4   | 18  |
| 7    | 0    | 17     | 21    | 4      | 11    | 7     | 2    | 8   | 12  |
| 8    | 1    | 44     | 63    | 7      | 6     | 7     | 11   | 32  | 42  |
| 9    | 14   | 44     | 67    | 25     | 32    | 22    | 21   | 51  | 101 |
| 10   | 0    | 15     | 26    | 1      | 2     | 4     | 3    | 38  | 41  |
| Mean | 2    | 29     | 42    | 8      | 12    | 10    | 6    | 20  | 34  |
| SD   | 4    | 14     | 18    | 7      | 11    | 9     | 6    | 16  | 28  |

OB-T = oddball targets
LG-CNS = local-global conflict no switch
LG-CS = local-global conflict switch
LG-NNS = local-global neutral no switch
LG-NS = local-global neutral switch
TM-MU = tone-monitoring memory update
TM-C = tone-monitoring control
S-C = Stroop congruent
S-I = Stroop incongruent
Figure Legend

Figure 1. Illustration of the electrodes used in the two frontal (a and b) and two parietal (c and d) ROIs.

Frontal

Parietal
The first frontal ROI (Figure 1a) included electrodes F3p, FZa, F4p, FC3, FZp, and FC4 and was used for the local-global N4 and Stroop N4. The second frontal ROI (Figure 1b) included electrodes F3p, FZp, F4p, FC3, CZp, and FC4 and was used for the tone-monitoring N3. The first parietal ROI (Figure 1c) included electrodes P3s, PZ, P4s, P3i, POZ, P4i, O1s, OZ, and O2s and was used for the local-global LPC and tone-monitoring P3. The second parietal ROI (Figure 1d) included electrodes P3i, PZ, P4i, O1i, POZ, O2i, O1i, OZ, and O2i and was used for the oddball P3b and Stroop LPC.

One parietal temporal window was extracted in the oddball task (P3b: 450-700 ms). Two temporal windows were extracted in the local-global task; one parietal (LPC: 350-600 ms) and one frontal (N4: 400-500 ms). Two temporal windows were extracted in the tone-monitoring task; one frontal (N4: 300-400 ms) and one parietal (P3: 300-700 ms). Two temporal windows were extracted in the Stroop task; one frontal (N4: 500-650 ms) and one parietal (LPC: 500-700 ms). Separate repeated-measures ANOVAs were performed for each component in each task with the mean amplitude per condition within each window averaged across the electrodes within each spatial ROI (separated by laterality) serving as the dependant measure. Waveforms for the ROIs (averaged across laterality) are shown for the oddball, local-global, tone-monitoring, and Stroop tasks and where there were laterality interactions with condition and group, average waveforms for left hemisphere, midline, and right hemisphere are shown; figures specified below (note that waveforms are plotted with inverted polarity, i.e. negative is up and positive is down). Significant effects and trends for the ERP components in the visual oddball, local-global, tone-monitoring, and Stroop tasks are detailed below. Group effects and trends for each of the components in the four tasks are summarized in Table 5.
Table Legend

Table 5. Summary of significant group ERP effects and trends in the oddball, local-global, tone-monitoring, and Stroop tasks. Significance level denoted as follows: * = < .05, and T for trend.

<table>
<thead>
<tr>
<th>Oddball</th>
<th>Local-global</th>
<th>Tone-monitoring</th>
<th>Stroop</th>
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<td><strong>P3b 450-700</strong></td>
<td><strong>LPC 350-600</strong></td>
<td><strong>N3 300-400</strong></td>
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<td>Stimulus X Condition X Group *</td>
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Visual Oddball Results

Behavioral Results

The RT and error data were analyzed using a between groups t-test. RT to targets did not significantly differ between control (M = 634, SD = 97) and ADHD (M = 633, SD = 80) subjects, p = .99. Errors were defined as either not responding to a target stimulus or responding to a standard or novel stimulus. There was no significant difference in the number of errors produced by control (M = 2, SD = 4) and ADHD (M = 5, SD = 7) subjects, p = .21.

Electrophysiological Results

P3b: 450-700: The data were analyzed using a 2 (Group: Control, ADHD) X 3 (Condition: Target, Standard, Novel) X 3 (Laterality: Left Hemisphere, Midline, Right Hemisphere) repeated measures ANOVA. There was a main effect for Condition, F (2, 36) = 17.69, p < .001, with the largest P3b for targets, the second largest for novels, and the smallest for standards. There was a trend for a main effect for Laterality, F (2, 36) = 2.66, p = .084, suggesting that the P3b was larger in the left and right hemispheres compared to the midline. There was a Condition X Laterality interaction, F (4, 72) = 9.12, p < .0001, indicating that the difference between novels and standards was larger in the left and right hemispheres compared to the midline. Average waveforms for the P3b are shown in Figure 2.

Visual Oddball Discussion

There were no group differences in the visual oddball task for the behavioral (RT and error) or ERP data, suggesting that ADHD children perform equally well on this task compared to controls both behaviorally and electrophysiologically. Furthermore, both
Figure Legend

**Figure 2.** Average waveforms for the P3b component in the visual oddball task.

- **ADHD**
  - Target
  - Standard
  - Novel
  - 2.0 μV

- **Control**
  - P3b
  - 450-700
groups showed the normal pattern associated with the P3b (450-700) with larger positivity to targets followed by novels and standards (Sutton et al., 1965, Courchesne et al., 1975). The P3b is a well-established ERP component associated with relevance processing. In the current sample, a trend suggested that the P3b was bilateral with greater differences between targets/novels and standards in left and right hemispheres compared to the midline, but there was no distinction between the central parietal P3b associated with orienting to task relevant, target stimuli and the more anterior and slightly earlier P3a elicited by novel stimuli. Unfortunately there was no differential processing to novel, task irrelevant stimuli as expected for the ADHD group due to their increased distractibility. This was possibly due to the relatively low number of novel trials available for analysis (by definition these stimuli are rare and occurred only 10% of the time resulting in only a potential 40 trials per subject for analysis).

Local-Global Results

Behavioral Results

The reaction time (RT) and error data were analyzed using a 2 (Group: Control, ADHD) X 2 (Stimulus: Conflict, Neutral) X 2 (Condition: Switch, No Switch) repeated measures ANOVA. There was a main effect for Group, F (1, 18) = 7.57, p = .013, with slower RTs for control subjects than ADHD subjects. There was a main effect of Stimulus, F (1, 18) = 36.46, p < .0001, with slower RTs for conflict compared to neutral stimuli. There was a main effect for Switch, F (1, 18) = 28.55, p < .0001, with slower RTs for the switch compared to no switch condition. There was a Stimulus X Group interaction, F (1, 18) = 7.58, p = .013, indicating that the difference between conflict and neutral stimuli was greater in controls than ADHD subjects (see Figure 3 for a bar graph).
Figure Legend

Figure 3. Stimulus X Group interaction for RT data in the local-global task.
Individual t-tests showed that the ADHD group was faster on conflict stimuli than the control group, \( t(18) = 3.41, p = .003 \), no difference between groups on neutral stimuli, \( p = .12 \), that control subjects were faster on neutral than conflict stimuli, \( t(9) = 7.28, p < .001 \), and a trend that ADHD subjects were faster on neutral than conflict stimuli, \( t(9) = 2.06, p = .07 \). There was a Stimulus X Condition interaction, \( F(1, 18) = 15.48, p < .001 \), indicating that the difference between conflict and neutral stimuli was greater for the switch compared to no switch condition. Errors were calculated by subtracting the number of correct responses from the total responses possible for each of the two conditions for each group. There was a main effect for Group, \( F(1, 18) = 7.33, p = .014 \), with more errors produced by ADHD than control subjects. There was a main effect for Stimulus, \( F(1, 18) = 90.23, p < .0001 \), with more errors produced for conflict compared to neutral stimuli. There was a main effect for Condition, \( F(1, 18) = 21.11, p < .0002 \), with more errors produced in the switch compared to no switch condition. There was a Stimulus X Condition interaction, \( F(1, 18) = 9.23, p = .007 \), indicating that the difference between conflict and neutral stimuli was greater in the switch compared to no switch condition.

Electrophysiological Results

LPC: 350-600: The data were analyzed using a 2 (Group: Control, ADHD) X 2 (Stimulus: Conflict, Neutral) X 2 (Condition: Switch, No Switch) X 3 (Laterality: Left Hemisphere, Midline, Right Hemisphere) repeated measures ANOVA. There was a main effect for Stimulus, \( F(1, 18) = 6.84, p = .018 \), indicating that the LPC was larger for neutral compared to conflict stimuli. There was a trend for a main effect for Condition, \( F(1, 18) = 3.9, p = .064 \), suggesting that the LPC was larger in the switch than no switch
condition. There was a Condition X Laterality interaction, $F(2, 36) = 4.35, p = .02$, indicating that the difference between the switch and no switch conditions was larger on the midline compared to the left and right hemispheres. There was a Stimulus X Condition X Laterality interaction, $F(2, 36) = 3.58, p = .038$, indicating that the difference between conflict and neutral stimuli was larger in the left and right hemispheres for the switch condition and larger on the midline for the no switch condition.

Due to different accuracy rates in the two groups, a separate analysis of the local-global data for the LPC component was conducted to evaluate the hypothesis that the ERP results from this task reflected different response strategies between the groups, with the control group emphasizing accuracy and the ADHD group emphasizing speed. To test this hypothesis the participants were separated into groups by task performance (high accuracy, low accuracy), rather than by clinical diagnosis (ADHD, control). This resulted in two ADHD participants being classified as high accurate and two control participants being classified as low accurate (see local-global discussion below).

**LPC: 350-600 (Resorted by task performance):** The data were analyzed using a 2 (Group: High Accuracy, Low Accuracy) X 2 (Stimulus: Conflict, Neutral) X 2 (Condition: Switch, No Switch) X 3 (Laterality: Left Hemisphere, Midline, Right Hemisphere) repeated measures ANOVA. The analysis resorted by task performance yielded four group effects. There was a trend for Stimulus X Group interaction, $F(1, 18) = 4.03, p = .056$, suggesting the LPC was larger for neutral than conflict stimuli in the low accuracy group but did not differ for the two conditions in the high accuracy group. There was a Condition X Group interaction, $F(1, 18) = 5.94, p = .025$, indicating that the
LPC was larger for the switch compared to no switch condition in the low accuracy group but did not differ between conditions in the high accuracy group. There was a trend for a Stimulus X Condition X Group interaction, $F(2, 36) = 3.69, p = .071$, suggesting that the LPC was larger for neutral compared to conflict stimuli in the no switch and switch conditions for the low accuracy group and only in the switch condition in the high accuracy group. There was a Stimulus X Condition X Laterality X Group interaction, $F(2, 36) = 4.19, p = .023$, indicating that the LPC was larger for neutral compared to conflict stimuli on the midline and right hemisphere in the no switch condition and on the right hemisphere in the switch condition for the low accuracy group with no differences between conditions in the high accuracy group.

**N4: 400-500:** The data were analyzed using a 2 (Group: Control, ADHD) X 2 (Stimulus: Conflict, Neutral) X 2 (Condition: Switch, No Switch) X 3 (Laterality: Left Hemisphere, Midline, Right Hemisphere) repeated measures ANOVA. There was a trend for a main effect for Group, $F(1, 18) = 4.18, p = .056$, suggesting that the N4 was larger for the ADHD compared to control group. There was a Stimulus X Condition X Group interaction, $F(2, 36) = 4.43, p < .05$, indicating that the N4 was more negative for neutral compared to conflict stimuli in the no switch condition for the control group and in the switch condition for the ADHD group (see Figure 4 for a bar graph). Average waveforms for the LPC and N4 are shown in Figure 5.

**Local-Global Discussion**

The ADHD subjects were faster than the control subjects on this task, but also produced significantly more errors suggesting they were more concerned with responding quickly than accurately. There was no difference in response times to conflict and
Figure Legend

Figure 4. Stimulus X Condition X Group interaction for the N4 in the local-global task.
Figure Legend

Figure 5. Average waveforms for the LPC and N4 components in the local-global task.

ADHD

Control

LPC
350-600

- Conflict No Switch
- Neutral No Switch
- Conflict Switch
- Neutral Switch

N4
400-500

2.0 uV
neutral stimuli for ADHD subjects, whereas controls were much slower to conflict stimuli. There were more errors for conflict stimuli for both ADHD and control subjects. Both groups responded slower and produced more errors overall on switch trials and to conflict compared to neutral stimuli on switch trials. The behavioral results suggest that the two groups used different strategies for this task with the control subjects focusing on accuracy and the ADHD subjects focusing on speed. Furthermore, the ADHD group was only slightly better than chance for the conflict switch and no switch producing 58 and 48 errors, respectively (out of 120 total trials, with chance being 60 errors). This suggests that ADHD subjects were unable to perform the task correctly and were most likely guessing. Overall the control subjects performed considerably better on the task based on the error data, but were also very impaired on conflict switch trials (42 errors) indicating that these trials in particular were difficult for both groups.

There was no difference in the local-global LPC (350-600) for the two stimuli types in control subjects, but the LPC was more positive for neutral than conflict stimuli in the ADHD subjects. This effect was not consistent with the behavioral data which showed that control subjects were slower for conflict stimuli but no difference for ADHD subjects. A possible explanation for this inconsistency between the behavioral and electrophysiological data is that there was no difference in the LPC for the control subjects because they performed the task correctly and consistently by switching from local to global or vice versa regardless of stimulus type. Although the ADHD subjects were unable to perform the task correctly with the conflict stimuli (as shown by the error data), they were considerably better with the neutral stimuli (only 28 and 26 errors for the neutral switch and no switch, respectively). It is possible that the ADHD subjects merely
responded to the letter they saw on the screen (i.e. when they saw a big "X" made of little "As" they just pressed "A" since "X" was not an option) instead of performing the task correctly by switching from local to global or vice versa with the neutral stimuli. The instructions were identical for both stimuli types, but it is reasonable that they used this strategy that enhanced their performance compared to the alternative guessing strategy utilized with the conflict stimuli. To test this hypothesis the local-global LPC data were resorted by task performance and reanalyzed. In summary, these findings showed that the LPC was larger for neutral stimuli in the low accuracy group with slightly different scalp distributions for the no switch and switch conditions. The difference in the LPC between the high and low accuracy groups is strong evidence that the two groups were using different strategies and that the LPC in the low accuracy group (similar to the ADHD group) represents a task relevance evaluation effect (discussed below).

Moreover, the results from this analysis support the hypothesis that the parietal positivity in the low accuracy group indexed a different cognitive process than in the high accuracy group, and that the ADHD participants, in general, adopted the low accuracy strategy. The interpretation that the groups were using different strategies was also supported by faster RTs for the ADHD compared to the control group, although the effect was non-significant, further suggesting the ADHD group were not performing the switch function for the neutral stimuli. The larger positivity for the LPC for neutral stimuli in the ADHD group therefore might represent a task relevance evaluation effect since the neutral stimuli had both relevant (i.e. As or Bs) and neutral or non-relevant (i.e. Xs) components, whereas both the local and global components were relevant in the conflict stimuli (As made of Bs or vice versa) resulting in the inability to perform the task. The LPC seen in
the control group is similar to the late (500-800) centroparietal positivity on switch trials compared to no switch trials in the WAIT task reported by Swainson et al. (2003). They interpreted this effect as indexing a reconfiguration of stimulus-response mapping signaled by a color cue, which is consistent with the current study that also used color to signal a response mapping switch. The LPC may index a post-response evaluation process from the preceding trial to reconfigure stimulus-response mapping for the control group since it appears the task was performed correctly based on the behavioral data. This interpretation is also consistent with Jackson et al. (2001) who reported a greater LPC (350-700) when switching between languages (not language specific) over bilateral parietal sites. The LPC in the current study is similar to the left lateraledized (no analysis of the midline was conducted) central P6 (450-750) reported by Kothmann and Potts (in preparation) which is consistent with the current data showing greater positivity for switch trials in the left compared to right hemisphere. The laterality effect for the P6 reported in their study was thought to represent greater response related motor activity since the effect was larger in the left hemisphere and subjects responded with their right hands. In the current data however, the midline showed the largest difference between the switch and no switch condition.

Functional MRI studies have show both frontal (Swainson et al., 2003) and left parietal (Sylvester et al., 2003) activations in task switching, however it can be difficult to separate temporally distinct activity in fMRI due to the relatively low temporal resolution of the hemodynamic response. It may be that the late parietal positivity seen by Swainson et al. (2003) and the midline/left lateralized LPC seen here correspond to
the left lateralized parietal activation seen in Sylvester et al. (2003) and relate to the instantiation of a new or alternate stimulus-response mapping.

In the local-global N4 (400-500) the neutral stimuli were more negative than the conflict stimuli in the no switch condition for the control group and in the switch condition for the ADHD group. The pattern shown by the ADHD group may represent an increase in attention allocation in order to perform the task switch and is consistent with previous findings of greater negativity during task switching (Moulden et al., 1998; Swainson et al., 2003). The N4 was larger for the neutral compared to conflict stimuli in the current task for both groups. RT and error data show that the ADHD group was at chance and the control group near chance for accuracy with the conflict stimuli, suggesting both groups were unable to perform the task with these stimuli. Therefore, the attention allocation operation performed on conflict trials was reduced compared to neutral trials. The finding that the effect was in the no switch rather than switch condition for the control group is inconsistent with previous findings and is possibly due to near chance performance on the conflict switch trials.

Tone-Monitoring Results

Behavioral Results

The RT and error data were analyzed using a 2 (Group: Control, ADHD) X 2 (Condition: Memory Update, Control) repeated measures ANOVA. There was a main effect for Condition, F (1, 18) = 21.15, p = .0002, with longer RTs for the memory update compared to control condition. Errors were calculated by subtracting the number of correct responses from the total responses possible for each of the two conditions for each group. There were no significant differences for errors. It was difficult to assess absolute
accuracy in this task. Once a participant made an error, their count would no longer match the absolute count for that tone. Therefore, for accuracy computation, the tone count was reset to 0 when the participant responded, whether or not that response was an error (subjects were informed of this during the task instructions and reminded before each block). Thus the accuracy count could be affected if the participant was aware of the mistake and attempted to compensate their count after an erroneous response.

**Electrophysiological Results**

**N3: 300-400:** The data were analyzed using a 2 (Group: Control, ADHD) X 2 (Condition: Memory Update, Control) X 2 (Trial Type: Response, No Response) X 3 (Laterality: Left Hemisphere, Midline, Right Hemisphere) repeated measures ANOVA. There was a main effect for Condition, F (1, 18) = 6.97, p = .017, with the N3 greater in the control than memory update condition. There was a main effect of Trial Type, F (1, 18) = 10.11, p = .005, with the N3 greater in the no response than response condition. There was a Laterality X Group interaction, F (2, 36) = 5.01, p = .012, indicating that the N3 was larger in the right hemisphere and midline than the left hemisphere in the control group and larger in the left and right hemisphere than the midline in the ADHD group. There was a Condition X Laterality interaction, F (2, 36) = 5.37, p = .009, indicating that the N3 was larger for the control than memory update condition in the left hemisphere and midline with no difference in the right hemisphere. There was a Trial Type X Laterality interaction, F (2, 36) = 5.79, p < .007, indicating that the difference between the response and no response condition was greater on the midline and left hemisphere than right hemisphere. There was a Trial Type X Laterality X Group interaction, F (2, 36) = 3.28, p < .05, indicating that the no response was greater than the response
condition in the left hemisphere and on the midline for the ADHD group and in the left hemisphere, midline, and right hemisphere for the control group (see Figure 6 for a bar graph and Figure 7 for average waveforms for left hemisphere, midline, and right hemisphere).

P3: 300-700: The data were analyzed using a 2 (Group: Control, ADHD) x 2 (Condition: Memory Update, Control) x 2 (Trial Type: Response, No Response) x 3 (Laterality: Left Hemisphere, Midline, Right Hemisphere) repeated measures ANOVA. There was a main effect for Condition, $F(1, 18) = 17.69$, $p < .0001$, with the P3 larger for the memory update than control condition. There was a main effect for Trial Type, $F(1, 18) = 20.07$, $p < .001$, with the P3 larger for response compared to no response trials. There was a main effect of Laterality, $F(2, 36) = 7.38$, $p = .002$, indicating that the P3 was larger on the midline and in the right compared to left hemisphere. There was a Trial Type x Laterality interaction, $F(2, 36) = 43.83$, $p = .031$, indicating that the difference between the response and no response trials was greater in the right and left hemispheres compare to the midline. Average waveforms for the N3 and P3 are shown in Figure 8.

Tone-Monitoring Discussion

Both groups were faster in the control compared to memory update condition and did not differ in the number of errors produced. As in the behavioral data, there were no group differences in the electrophysiological data for the P3. The P3 was larger in the memory update than control condition and likely represents the well-described P3 working memory updating effect described by Donchin (1981) and shown recently in a similar design by Kiss et al. (1998) and Kothmann and Potts (in preparation). The P3 also showed greater positivity on the response trials, compared to the no response trials,
Figure Legend

**Figure 6.** Trial Type X Laterality X Group interaction for the N3 in the tone-monitoring task.
Figure Legend

**Figure 7.** Average waveforms for left hemisphere, midline, and right hemisphere for the N3 component in the tone-monitoring task.

---

ADHD

**Left Hemisphere**

2.0 uV

N3

300-400

**Midline**

**Right Hemisphere**

--- Memory Update Response
--- Memory Update No Response
--- Control Response
--- Control No Response
Figure Legend

Figure 8. Average waveforms for the N3 and P3 components in the tone-monitoring task.

- Memory Update Response
- Memory Update No Response
- Control Response
- Control No Response

N3
300-400

P3
300-700
perhaps related to the classic P3b task relevance effect (larger P3 on trials requiring a response) (Courchesne et al., 1975). A similar relevance effect was also reported by Kothmann and Potts (in preparation) for their parietal P3 (300-400) component.

There were two group effects in the N3 (300-400) component. The N3 was bilateral for the ADHD subjects with reduced amplitude on the midline, but more negative in the right hemisphere and on the midline for the control subjects. The N3 was more negative for no response trials, particularly for the ADHD group on the midline. This pattern shown by the ADHD group (N3 more negative on no response trials) is consistent with the parietal N4 (400-540) reported by Kothmann and Potts (in preparation) and interpreted as a task difficulty effect with the more cognitively demanding conditions (response trials) more positive, although the current N3 was located in the frontal region. The N3 reported here was also earlier than the parietal N4 reported in our previous study. These differences in localization and latency may be due to differences in the two tasks. The updating task used in the current study was considerably easier, requiring updating of two memory buffers after the presentation of two like tone types, whereas the task in the previous study required updating of three memory buffers after the presentation of four like tones. Therefore in the current less difficult working memory task, subjects were able to perform the updating operation faster.

Overall the results for the N3 are consistent with the well-described frontocentral N2 that is larger on trials in which a response is withheld (no-go) compared to trials on which a response is executed (go) (Bokura et al., 2001; Kopp et al., 1996). Therefore this component appears to be related to response inhibition. An alternate explanation of this
component, since the tone-monitoring task was the only executive task in which some stimuli did not require an overt response, is that this enhancement may be the negative effect related to the ‘relevance’ P3b, seen to stimuli that require a response (as in the oddball task), volume conducted over the frontal leads.

**Stroop Results**

**Behavioral Results**

The RT and error data were analyzed using a 2 (Group: Control, ADHD) X 2 (Condition: Congruent, Incongruent) repeated measures ANOVA. There was a main effect for Condition, F (1, 18) = 44.1, p < .0001, with RTs longer in the incongruent compared to congruent condition. Errors were calculated by subtracting the number of correct responses from the total responses for each of the two conditions for each group. There was a main effect for Condition, F (1, 18) = 5.15, p = .036, with more errors produced in the incongruent than congruent condition.

**Electrophysiological Results**

**N4: 500-650:** The data were analyzed using a 2 (Group: Control, ADHD) X 2 (Condition: Incongruent, Congruent) X 3 (Laterality: Left Hemisphere, Midline, Right Hemisphere) repeated measures ANOVA. There was a main effect for Condition, F (1, 18) = 4.75, p < .043, with the N4 greater for the incongruent compared to congruent condition. There was a Condition X Laterality X Group interaction, F (2, 36) = 3.17, p = .054, indicating that the N4 was greater for the incongruent than congruent condition on the midline in the control group and larger in the right hemisphere in the ADHD group (see Figure 9 for a bar graph and Figure 10 for average waveforms for left hemisphere, midline, and right hemisphere).
Figure Legend

Figure 9. Condition X Laterality X Group trend for the N4 in the Stroop task.
Figure Legend

Figure 10. Average waveforms for left hemisphere, midline, and right hemisphere for the N4 component in the Stroop task.

ADHD

Control

Left Hemisphere

Midline

Right Hemisphere

——— Congruent

——— Incongruent
LPC: 500-700: The data were analyzed using a 2 (Group: Control, ADHD) X 2 (Condition: Incongruent, Congruent) X 3 (Laterality: Left Hemisphere, Midline, Right Hemisphere) repeated measures ANOVA. There was a main effect of Condition, $F(1, 18) = 4.56, p = .047$, with the LPC larger for the incongruent compared to congruent condition. There was a main effect of Laterality, $F(2, 36) = 3.28, p < .05$, with the LPC larger in the left hemisphere followed by the midline and right hemisphere. Average waveforms for the N4 and LPC are shown in Figure 11.

Stroop Discussion

Both groups were slower and made more errors on incongruent compared to congruent stimuli and therefore showed the classic Stroop effect. There were no group effects in the LPC (500-700) component. In both groups the LPC was larger to incongruent stimuli and left lateralized. This effect is similar to the central P6 shown in Kothmann and Potts (in preparation) and may represent a response evaluation of the trial outcome, which is more critical in the incongruent condition due to the inherent conflict.

The N4 (500-650) was larger for the incongruent compared to congruent condition in the right hemisphere electrodes in the ADHD group. The N4 may be associated with inhibition of a response due to the conflicting semantic information from the decoded word-form. The latency of the current N4 is later than the classic N4 reflecting semantic expectancy that peaks around 400 ms post stimulus, but is generally consistent showing more negativity in the incongruent condition (N4 is usually the difference between incongruent and congruent trials). An alternate explanation of this component, since the latency is similar to the LPC in this task, is that this negativity is related to response evaluation of trial outcome which is more critical for incongruent
Figure Legend

Figure 11. Average waveforms for the N4 and LPC components in the Stroop task.

ADHD

Control

2.0 uV

N4

500-650

LPC

500-700

Congruent

Incongruent
trials, volume conducted over the frontal leads.

The significant effects seen in the Stroop task were a larger N4 and LPC in the incongruent (conflict) condition. This pattern of a negativity followed by a later positivity is similar to inhibition ERP findings reported by Liotti et al. (2000) and Kiefer et al. (1998), although localization of the components comprising this negative/positive pattern has varied between studies. Using the Stroop design, Liotti et al. (2000) reported the early negativity in the anterior medial or broad dorsal region, depending on the task (verbal or manual response) followed by a late positivity in the left superior temporoparietal region. Using a go/no-go paradigm, Kiefer et al. (1998) reported an early negativity over frontal regions followed by a later positivity over the frontocentral region. This pattern (early negativity followed later positivity) was also found in Kothmann and Potts (in preparation), although the N4 was a posterior component in their study and is over frontal regions in the current study. The discrepancies between these findings suggest that the negative-positive ERP inhibition effect is sensitive to task manipulations (variations and proportions of incongruent, congruent, and neutral stimuli), however, the pattern of results seen here is generally consistent with Liotti et al. (2000), with a dorsal negativity followed by a temporoparietal positivity in their study and a frontal negativity and a parietal positivity in the current study.

**General Discussion**

The current experiments explored differential processing in ADHD and control children on three executive function tasks that evaluated task switching, working memory, and response inhibition and one non-executive function control task that evaluated target detection. There were no group differences in the parietal positive components for all of the four tasks (oddball P3b, local-global LPC, tone-monitoring P3,
or Stroop LPC). The P3b in the visual oddball task appears to index relevance processing, being larger to targets/novels than standard stimuli, and is consistent with the classic P300 or P300b component first described by Sutton et al. (1965) in which targets produce a large amplitude ERP component, with a topographical distribution over posterior scalp regions. The LPC in the local-global task may index a task relevance evaluation effect in the ADHD group, being larger for neutral stimuli which had both relevant (i.e. As or Bs) and neutral or non-relevant (i.e. Xs) components, whereas the LPC seen in the control group may index a post-response evaluation process from the preceding trial to reconfigure stimulus-response mapping, and is consistent with the late centroparietal positivity during switching reported by Swainson et al. (2003) and Jackson et al. (2001). The P3 in the tone-monitoring task appears to index working memory updating, being larger in the high memory load condition, and is consistent with the well-defined posterior positivity that is elicited during tasks that require updating the contents of working memory described by Donchin (1981) and shown more recently by Kiss et al. (1998) and Kothmann and Potts (in preparation). The LPC in the Stroop task appears to index response evaluation of trial outcome, being larger in the incongruent condition and more critical due to the inherent conflict, and is consistent with the late central positivity reported by Kothmann & Potts (in preparation).

Since the oddball P3b, local-global LPC, tone-monitoring P3, and Stroop LPC were of equivalent amplitude in the ADHD and control groups, relevance processing, stimulus-response reconfiguration, working memory updating, and response evaluation of trial outcome do not appear impaired in this ADHD group. These findings are at odds with much of the behavioral literature and symptomatology in ADHD that indicate poorer
performance on various working memory tasks, switching tasks (although the current
tasks have not been previously used) and inhibition paradigms including the Stroop task.
Perhaps either the small group size in the current study did not adequately represent the
ADHD population, or the current tasks, modified from a study originally designed to
create maximal distinction between executive functions, was not an optimal assessment
of these cognitive operations. As mentioned earlier the oddball task has not previously
been used in the ADHD population, but the null finding here is generally consistent with
the findings of intact processing on a variety of non-executive function tasks in ADHD
(Pennington & Ozonoff, 1996). Although the LPC in the local-global failed to show
group differences, the behavioral data suggests that the task was too difficult for the
ADHD subjects, who appeared unable to perform the task appropriately, likely
compromising the electrophysiological results. Recall that the ADHD group performed
at chance for the conflict stimuli but made considerably fewer errors on the neutral trials
and appeared to be responding to the relevant component of the stimuli without
performing the switch function. It is unclear whether or not the differences seen in the
local-global LPC represent an impairment in the ADHD group related to executive
functioning (such as an inability to perform the switch function) or if the current finding
reflects poor performance due to task difficulty. Moreover, previous behavioral studies
reviewed by Pennington & Ozonoff (1996) found inconsistencies in the WCST, albeit a
more complex task used to measure the switch function, suggesting that
electrophysiological findings associated with this executive function may similarly be
unreliable.
Although the aforementioned components suggest intact processing on the non-executive control task and some cognitive operations associated with the executive tasks for the ADHD group, the current findings indicate that is not the case for all the executive functions. There were group differences in the frontal negative components for all three executive function tasks, the local-global N4, the tone-monitoring N3, and the Stroop N4, all of which were differentially impacted in the ADHD group. The N4 in the local-global task, which appears to index allocation of attention, being larger to the neutral switch condition in the ADHD group (recall that the ADHD group were unable to perform the task with the conflict stimuli so no attention operation was necessary), is consistent with greater negativity during task switching (Moulden et al., 1998; Swainson et al., 2003). The N3 in the tone-monitoring task, which appears to index response inhibition, being larger on no response trials, and is consistent with the classic frontocentral N2 that is larger on trials in which a response is withheld (no-go) compared to trials on which a response is executed (go) (Bokura et al., 2001; Kopp et al., 1996). Overall the ADHD group showed reduced amplitude compared to the control group for the tone-monitoring N3, suggesting impairment in the ability to accurately identify how difficult a task is going to be to appropriately allocate processing resources. The N4 in the Stroop task appears to index response inhibition, specifically inhibition of conflicting semantic information, being larger in the incongruent condition, consistent with the frontal negativity reported by Liotti et al. (2000) and Kiefer et al. (1998) using the Stroop and go/no-go tasks to evaluate response inhibition, respectively. The overall amplitude for the N4 was not reduced for the ADHD group compared to the controls (actually slightly larger), which is inconsistent with previous findings (Liotti et al., 2005). However, the
current findings do suggest possible differences in the neural organization of the inhibition function in the ADHD and control brain based on laterality differences in the N4 component between the groups. The control group showed an N4 that was more equally distributed across the midline and right and left hemisphere electrodes, while the N4 in the ADHD group was largest in the right hemisphere, suggesting a more focal spatial distribution of the component. This could indicate less brain area and/or fewer neural resources devoted to behavioral inhibition in the ADHD group.

Task performance (accuracy) on the local-global task with the conflict stimuli was at chance for the ADHD group and near chance on the conflict switch trials for the control group. As with the parietal LPC component in the local-global task, it cannot be determined from the present data if the frontal N4 and its respective cognitive operation would have produced similar results in a version of the task in which the ADHD subjects were able to perform correctly.

Since the local-global N4, tone-monitoring N3, and Stroop N4 were NOT of equivalent amplitude in the ADHD and control groups (reduced amplitude on at least one or more of the conditions for the ADHD compared to control group), attention allocation and response inhibition (in both the tone-monitoring and Stroop tasks) appear impaired in this ADHD group. These findings are consistent with the majority of the behavioral literature and symptomatology in ADHD that indicate deficits on a variety of executive function tasks requiring allocation of attention and inhibition tasks such as the Stroop task, a general hypothesis of frontal lobe dysfunction in ADHD (Pennington & Ozonoff, 1996), and fMRI findings that have shown subnormal activation of the prefrontal systems in ADHD subjects (Katya et al., 1999).
Taken together, these findings suggest that children with ADHD have preserved functioning on tasks that involve relevance processing, stimulus-response reconfiguration, working memory updating, and response evaluation of trial outcome but are impaired on tasks involving allocation of attention and response inhibition. Thus, the conclusion from the current findings is that ADHD impacts only this subset of executive functions, leaving the other ERPs in the executive tasks and the visual oddball unaffected. The current findings are consistent with the symptomatology of Combined Type ADHD characterized by inattention, impulsivity, and hyperactivity. The impaired cognitive operations in the executive function tasks (i.e., allocation of attention and inhibition) are those most closely related to the diagnostic criteria for this subtype of ADHD. Based on these findings, one may speculate that the predominantly Inattentive Type would show the attention allocation deficits (e.g. amplitude reduction in the tone-monitoring N3 component) while the predominantly Hyperactive-Impulsive Type would show the inhibition deficits (e.g. amplitude reduction in the tone-monitoring N3 component and spatial reduction in the Stroop N4 component). The current study described ERP components with response properties consistent with indexes of two general component cognitive operations (allocation of attention and response inhibition) that seem to differentiate between ADHD and control subjects. The frontal negative components which are the most sensitive to these cognitive operations were most unambiguously affected in the ADHD group in the executive function tasks.

Limitations

The current study used only one task for each of the executive functions, due to time limitations of the ERP method, where Miyake et al. (2000) used three for each
function in order to rule out extraneous variables. The three executive experiments described here used different stimuli for each executive function (and in one case in a different modality), thus the current study cannot dissociate executive effects and stimulus effects, and thus cannot directly address executive functions across tasks. Differential performance in some of the tasks between the groups suggests that the ERP components used may not provide a direct comparison of the same cognitive function between groups. The study also had a relatively small sample size, which may have limited the number of significant group differences.

This study used experimental designs adapted from Miyake et al. (2000), designs to differentially engage three separate executive functions: switching, updating, and inhibition. The ERP results were consistent with previous studies that independently investigated the executive functions, and provided a foundation on which to explore the separability of those executive functions. Future research may employ a design in which the stimulus materials are held identical across tasks that differentially engage the three executive functions, and only the instructions would change (task difficulty would be better controlled), provide tasks in which both groups employ the same performance strategy, and include more subjects. Further investigation on executive processing in children with ADHD should also be extended to the predominantly Inattentive and Hyperactive-Impulsive Types in order to better understand the relationship between the symptomatology and cognitive deficits associated with this prevalent neurobehavioral disorder. These modifications may provide independent measures of the time course and localization of specific executive functions and may ultimately provide a method for more fully defining the nature of disrupted executive functioning in ADHD.
References


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