

2
2002



This is to certify that the
dissertation entitled

Selective Attention in ADHD Subtypes

presented by

Cynthia L. Huang-Pollock

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Psychology

Major professor

Date 12/14/01

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.
MAY BE RECALLED with earlier due date if requested.

DATE DUE	DATE DUE	DATE DUE

SELECTIVE ATTENTION IN ATTENTION DEFICIT HYPERACTIVITY
DISORDER SUBTYPES

By

Cynthia L. Huang-Pollock

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Psychology

2001

ABSTRACT

SELECTIVE ATTENTION IN ATTENTION DEFICIT HYPERACTIVITY DISORDER SUBTYPES

By

Cynthia Leigh Huang-Pollock

The moderating effect of perceptual load on visual selective attention was examined in three studies. In Study 1, children and young adults searched central displays of varying set size flanked by irrelevant peripheral distractors. Children's performance was as efficient as adults' under conditions of high but not low loads, suggesting that early selection engages early maturing neural systems, and late selection engages later maturing neural systems. In Study 2, four age groups were tested to better describe the development of selective attention, and placemarkers were set at the empty locations to examine perceptual grouping effects. Study 1's pattern replicated in all age groups, with onset of early selection occurring at lower loads for younger children.

Having established the perceptual load paradigm's properties and validity in children, Study 3 utilized this paradigm to examine early and late selective attention processes in children with the primarily inattentive (ADD-H) and combined subtypes (ADD+H) of Attention Deficit Hyperactivity Disorder (ADHD). Potential response modulation and arousal deficits were also examined. Results were mixed, but suggested the presence of an early selective attention deficit in children with ADD-H and ADD+H. Evidence for a interference control deficits, at least in boys with ADD+H, was also present. Results are discussed in relation to theories of cognitive and neural development, and the ramifications for neuropsychological theories of ADHD.

for my grandmother

ACKNOWLEDGEMENTS

I would first like to express my deepest gratitude to my advisor, Joel Nigg, who has supported, encouraged, and cheered my academic, intellectual, and personal growth for the last six years. I continually strive towards the examples he has set of mentor, teacher, theorist, researcher, and clinician.

I would also like to thank the members of my committee, Norman Abeles, Thomas Carr, and Anthony Nunez, for their continuing guidance and enthusiasm for my endeavors. In addition to their service on my committee, they have been inspirational teachers, and I have been privileged to know and to work with them.

However, none of this would be possible without the love of my friends and my family, two-legged and four-legged alike. They have held me up and believed in me throughout this long journey. And to my husband Alex who walked every step of the road with me: your joy in my accomplishments and your faith in my success, your steadfastness in times of sorrow, and your commitment to our future, has made everything bright.

I remain truly blessed.

TABLE OF CONTENTS

Introduction_____	1
Clinical Description of ADHD_____	1
Theoretical Explanations of ADHD_____	3
Plan for this Essay_____	5
Models of Selective Attention_____	5
Critique of the Perceptual Load Paradigm_____	10
Inattention in ADHD_____	12
ADHD and perceptual load_____	13
ADHD and attentional capacity_____	15
ADHD and early selective attention_____	17
Late Selective Attention_____	24
ADHD and late selective attention_____	25
ADHD and response modulation_____	26
Selective Attention and Response Modulation in relation to the Perceptual Load Model_____	28
Arousal and State Regulation_____	29
ADHD and arousal_____	31
Summary_____	35
Study 1_____	35
Existing Evidence on Development of Selective Attention_____	35
Aims and Hypotheses for Study 1_____	38
Method_____	39

Participants	39
Procedure	40
Data Analysis	43
Results	43
Discussion	48
Study 2	49
Aims and Hypotheses	50
Method	51
Participants and Procedures	51
Results	51
Discussion	56
General Discussions of Studies 1 and 2	58
Summary of Studies 1 and 2	61
Study 3	61
Methods	63
Participants	63
Procedures	67
Measures	68
Diagnostic Questionnaires	68
Cognitive Screening Measures	70
Selective Attention Paradigm	71
Sample Size and Power Analysis	71
Data Reduction and Analysis	72

Results	73
Discussion	84
Conclusion	92
References	94
Tables	105
Figures	112
Appendix I. Neurochemical and Physiological Evidence of an Inhibitory Deficit in ADHD	140
Appendix II. Neurochemical and Physiological Evidence of an Arousal Deficit in ADHD	143
Appendix III. Behavioral and Cognitive Screening Procedures	145

LIST OF TABLES

Table 1:	Summary of the perceptual load model of selective attention_____	105
Table 2:	Mean reaction time in ms (SD) to correct target identification and percentage errors (SD) for Study 1_____	106
Table 3:	Mean reaction time in ms (SD) to correct target identification and percentage errors (SD) for Study 2_____	107
Table 4:	Analysis of variance for child age groups in Study 2_____	108
Table 5:	Description of groups prior to removal of children with high errors in Study 3_____	109
Table 6:	Description of final groups for Study 3_____	110
Table 7:	Mean reaction time in ms (SD) to correct target identification and percentage errors (SD) for Study 3_____	111

LIST OF FIGURES

Figure 1:	Example displays with high and low perceptual loads_____	112
Figure 2:	Example of stimuli from a flanker-type task_____	113
Figure 3:	Example of a two and eight-letter display from Miller's (1991) Study _____	114
Figure 4:	Schematic descriptions of sustained attention and arousal deficits on a generic task_____	115
Figure 5:	Progression of stimuli_____	116
Figure 6:	Reaction time interference effects for Study 1. Standard error bars displayed_____	117
Figure 7:	Percentage error interference effects for Study 1. Standard error bars displayed_____	118
Figure 8:	Example display for Study 2 under conditions of low load (set size = 2) with the neutral distractor "L" _____	119
Figure 9:	Reaction time interference effects for Study 2. Standard error bars displayed_____	120
Figure 10:	Percentage error interference effects for Study 2. Standard error bars displayed_____	121
Figure 11:	Reaction time interference effects with and without placemarkers. Standard error bars displayed_____	122
Figure 12:	Percentage error interference effects with and without placemarkers. Standard error bars displayed_____	123
Figure 13:	Schematic descriptions of the pattern of results if ADHD represents a deficit in (a) early selective attention, (b) late selective attention, (c) response modulation, or (d) arousal_____	124
Figure 14:	Frequency of responses to incorrect target identification and omission errors occurring in 100 ms intervals for children were and were not able to maintain a 60% accuracy rate, collapsed across diagnostic groups_____	125
Figure 15:	Frequency of responses to correct target identification occurring in	

	100 ms intervals for children who were and were not able to maintain a 60% accuracy rate, collapsed across diagnostic groups	126
Figure 16:	Frequency of response to incorrect target identification and omission errors occurring in 100 ms intervals for children who were and were not able to maintain a 60% accuracy rate, broken down by diagnostic groups	127
Figure 17:	Frequency of response to correct target identification occurring in 100 ms intervals for children who were and were not able to maintain a 60% accuracy rate, broken down by diagnostic groups	128
Figure 18:	Reaction time interference effects by diagnosis for Study 3. Standard error bars displayed	129
Figure 19:	Percentage error interference effects by diagnosis for Study 3. Standard Error bars displayed	130
Figure 20:	Reaction time interference effects by sex for Study 3. Standard error bars displayed	131
Figure 21:	Percentage error interference effects by sex for Study 3. Standard error bars displayed	132
Figure 22:	Percentage errors committed by diagnosis and sex for Study 3. Standard error bars displayed	133
Figure 23:	Reaction time interference effects for control and ADD+H boys for Study 3. Standard error bars displayed	134
Figure 24:	Percentage error interference effects for control and ADD+H boys for Study 3. Standard error bars displayed	135
Figure 25:	Mean reaction time across time by diagnosis for Study 3. Standard error bars displayed	136
Figure 26:	Mean standard deviation across time by diagnosis for Study 3. Standard error bars displayed	137
Figure 27:	Percentage errors and omissions across time by diagnosis for Study 3. Standard error bars displayed	138
Figure 28:	Standard deviation by diagnosis across set size for Study 3. Standard error bars displayed	139

Introduction

Clinical Description of ADHD

Childhood Attention Deficit Hyperactivity Disorder (ADHD) is a serious, common, and chronic behavioral syndrome characterized by impaired attention, impulsivity, and excessive motor activity (APA, 1994). There are three subtypes as currently defined. Approximately 85% of those referred for clinical purposes are diagnosed as combined subtype (ADD+H) as opposed to the primarily inattentive subtype (ADD-H), although the inattentive type is more common in population surveys (Barkley, 1996). The primarily hyperactive subtype (APA, 1994), is rare and is chiefly observed in preschool children (Barkley, 1996). It is excluded from the current research. Although psychosocial influences doubtless affect the expression of childhood behavioral disorders, extensive evidence supports the role of neuro-cognitive mechanisms in ADHD. Patterns of performance on tasks measuring specific cognitive functions may therefore differentiate non-ADHD from ADHD children, as well as ADHD subtypes, thus contributing clues to differential etiology in these groups.

Complicating the process of research, however, are the changing phenotypic descriptions and diagnostic criteria of the disorder. Whereas DSM-III (APA, 1980) included subtypes of ADHD with and without hyperactivity, DSM-III-R (APA, 1987) removed this distinction and described ADHD as a unitary disorder of inattention, hyperactivity, and impulsivity (Faraone, Biederman, Weber, & Russell, 1998). Following field trial investigations supporting a two-factor structure to ADHD symptoms (inattention-disorganization vs. hyperactivity-impulsivity) and clinically meaningful differences between subtypes, DSM-IV (APA, 1994) returned to subtyping (Faraone et

al., 1998).

Diagnoses are established behaviorally. Diagnosis of ADHD combined subtype, requires six symptoms of hyperactivity/ impulsivity and six symptoms of inattention. Diagnosis of ADHD, inattentive subtype, requires 6 symptoms of inattention, but fewer than 6 symptoms of hyperactivity/impulsivity. Symptoms of hyperactivity include often: fidgeting with hands or squirming in seat, leaving seat in situations in which it is inappropriate, running about or climbing excessively in situations in which it is inappropriate, difficulty playing or engaging in leisure activities quietly, “on the go” or acting as if “driven by a motor,” talking excessively, blurting out answers before questions have been completed, difficulty awaiting turn, and interrupting or intruding on others. Symptoms of inattention include often: failing to give close attention to details or making careless mistakes in tasks, having difficulty sustaining attention in tasks or play, not seeming to listen when spoken to directly, not following through on chores or duties, having difficulty organizing tasks and activities, avoiding, disliking, or reluctantly engaging in tasks requiring sustained mental effort, losing things necessary for activities, easily distracted by extraneous stimuli, and forgetful in daily activities.

Children with the combined subtype are rated as more aggressive, socially rejected, and demonstrate greater impairment in multiple domains than the inattentive subtype. Children with the inattentive subtype have an older age of onset, are rated as more shy, anxious, and are more likely to experience academic difficulties than the combined subtype (Barkley, DuPaul, & McMurray, 1990; Faraone et al., 1998). It is important to be aware, however, that some children classified as primarily inattentive also have hyperactive symptoms which are shy of cutoffs for the combined subtype.

Furthermore, recent research has suggested that a hypoactive/sluggish subgroup of the inattentive subtype may exist and that they may differ cognitively from non-hypoactive inattentive children (McBurnett, Pfiffner, & Frick, 2001).

Methodological concerns in ADHD research also concern potential sex effects. Girls with ADHD tend to cluster into the primarily inattentive subtype, exhibit lower levels of hyperactivity and fewer externalizing behaviors than boys with ADHD (Gaub & Carlson, 1997). However, it is likely that psychosocial influences play a role in the development of behavior and of behavioral distinctions within and between subtypes. Thus, an examination of possible sex effects is important in any research concerned with cognitive mechanisms in subtypes of ADHD.

Further, it is now recognized that better control of comorbid disorders is needed in evaluating ADHD deficits. Without such controls, the inclusion of children with comorbid disorders may obscure the cognitive dysfunctions specifically associated with ADHD (Nottlemann & Jensen, 1995). It has also been suggested that the presence of certain comorbid disorders such as anxiety or conduct disorder may represent distinct subtypes of ADHD with separate etiologies, risk factors, and outcomes (Biederman, Newcorn, & Sprich, 1991; Jensen 1997; Nigg, 2001). These considerations may help to explain discrepant findings across research in ADHD.

Theoretical Explanations of ADHD

As its name implies, ADHD has been thought for at least two decades to represent a possible deficit in attention, although the concept of “attention” within the clinical literature has not been clearly defined. Whereas behavioral ratings from parents and teachers are able to consistently and reliably differentiate the two subtypes (Lahey,

Applegate, McBurnett, & Biederman, et al., 1994; McBurnett, Pfiffner, Willcutt, & Tamm, et al., 1999), understanding of the cognitive mechanisms, if any, underlying this differentiation is speculative at best. Thus, the controversy over whether formally-defined attentional processes are indeed dysfunctional in ADHD (Barkley, 1997b) is complicated by the ambiguity between the behavioral descriptions provided by parents and teachers, and the neurocognitive mechanisms which may or may not underlie these behaviors. Neuropsychological and neuroimaging studies suggest that children with the combined subtype of ADHD have deficits in the prefrontal cortices and associated basal ganglia structures (Barkley, 1997b; Lou, Henriksen, & Bruhn, 1984). On the other hand, there have also been suggestions that children with the primarily inattentive subtype differ in etiology from the combined subtype and suffer from deficits in the posterior parietal cortices (Barkley, DuPaul, & Murray, 1990; Goodyear & Hynd, 1992).

Some ADHD theorists have suggested that primary dysfunctions in executive (Barkley, 1997b), or arousal systems (Zentall & Zentall, 1983) may account for the behavioral symptoms of “inattention.” Others have proposed that suboptimal activation or allocation of effort during motor output is primary to the disorder (Sergeant, Oosterlaan, & van der Meere, 1999). In contrast, in a recent review, Douglas (1999) argued that insufficient allocation of effort leads to attentional (i.e. perceptual or early-stage processing) as well as inhibitory (central processing) deficits, and is not restricted to motor output stage alone. She argued that further evaluation of possible attentional dysfunctions in ADHD was essential. Indeed, key ADHD theorists such as Douglas (1999) versus Sergeant et al. (1999) differ fundamentally regarding the status of attention, and particularly selective attention, in ADHD. Determination of whether inattention is

indeed a cognitive (and not merely behavioral) hallmark in ADHD would enable better theory development and is essential to evaluating current theories of ADHD.

The first step in this a process would be to utilize more clearly defined neurocognitive as opposed to behavioral constructs of “attention,” as well as to specify which of the multiple types of attention are under examination. Furthermore, any one or all of the above processes (e.g. arousal, effort, central or perceptual processing deficits) could be related to or impact attentional processing. This point is illustrated subsequently in relation to arousal and inhibitory control processes.

Plan for this Essay

I first describe current models and understanding of selective attention. Because of their importance to integrating the proposed work with the rest of the ADHD literature, and their potential impact on and relation with attentional functioning, I also discuss the constructs of inhibition and arousal. This is followed by a discussion of relevant experimental findings in children with ADHD. Based on this review, a cognitive deficit model of the two primary ADHD subtypes is proposed. During this discussion, ADD+H will be used to refer to the DSM-IV combined subtype, ADD-H to the inattentive subtype, and ADHD to affected children as a whole regardless of subtype. Because most studies used earlier definitions of ADHD, generally without reference to subtype, “ADHD” is used to refer to those samples.

Models of Selective Attention

As its name implies, selective attention is defined as the ability to attend to one source of information while ignoring others (Portas, Rees, Howseman, Josephs, Turner, & Frith, 1998). The construct of selective attention is based upon the idea that the

perceptual world presents too much information for a limited capacity system to process. Therefore, an act of selection must occur at some point in processing, and only some of the available information is processed beyond this point. Whether selection takes place relatively early or late in the temporal sequence of information processing has been vigorously debated.

Two prominent points of view compete on this matter: the early and late selection approaches. Broadbent (1958), a proponent of the early selection approach, argued that selection occurs early in the chain of processing, following a brief and incomplete analysis of physical features and prior to semantic analysis and identification. According to this view, the later stages of perception involved with semantic analysis and identification are severely limited in capacity, and can only handle a small number of stimuli at a time. Thus, unattended stimuli are not fully perceived and hence these later stages are protected from overload. In contrast, proponents of the late selection approach argue that perception occurs automatically, has an unlimited capacity, and proceeds in parallel without the need for selection (Deutsch & Deutsch, 1963). In this latter model, selection operates only after semantic identification, and is primarily concerned with what decisions to make and what responses to produce.

There is an important distinction between these two conceptualizations of “selection.” That is, Broadbent (1958)’s early-selection model refers specifically to the selection of information from the external, perceptual features such as color, shape, or spatial location. On the other hand, Deutsch and Deutsch’s (1963) late-selection model is concerned with the selection of internally represented information based on task demands. These two processes appear to be distinct and separable neuroanatomically as

well as computationally. Selection based upon perceptual features most likely involves a largely posterior network of brain structures including regions of parietal and tempoparietal cortex (Arrington, Meyer, Carr, & Rao, 2000; Corbetta, 1998; Friedrich, Egly, Rafal, & Beck, 1998; Gitelman, Nobre, Parrish, LaBar, Kim, Meyer, & Mesulam, 1999; Posner & Raichle, 1994). On the other hand, a review of PET studies has suggested that selection of internal representations, as measured by Stroop-like tasks (MacLeod, 1991), involves a largely anterior network including the anterior cingulate gyrus and various regions of prefrontal cortex (Barch, Braver, Sabb, & Noll, 2000; Cabeza & Nyberg, 1997; Ziegler, Besson, Jacobs, Nazir, & Carr, 1997).

To add to this debate, recent research with adults suggests that the locus of selection (i.e. early versus late) is a function of the perceptual load on the attentional system (Lavie, 1995; Lavie & Cox, 1997; Lavie & Fox, 2000; Lavie & Tsal, 1994). When perceptual load is low, selection relies on processes that respond to semantic features (and are likely under the control of the anterior network) and occurs late, after considerable processing has already been accomplished. This allows most or all of the stimuli available to the senses to be identified, and to influence decision making and response selection. On the other hand, when the perceptual load is high, selection shifts and comes under the control of processes that respond to perceptual features (likely under the control of the posterior network). The locus of selection in this case is early, reducing the number of stimuli that are processed deeply enough to be identified and to compete for control of action. Table 1 summarizes the perceptual load model.

Lavie and Tsal (1994) define the concept of “load” as consisting of two separate components: (1) the number of potentially task-relevant items in a display and (2) the

nature of the processing required for each item. That is, the more task-relevant items in a display and/or the greater effort required to process the display, the higher the load. Note that the number of units does not refer to actual physical units, but rather to the number of perceptual units determined by task instructions (Lavie & Tsal, 1994). For example, a string of letters may either serve as one unit (a word), or several units (letters), depending upon whether the task requires a response to a word, or to a letter (Lavie & Tsal, 1994). Figure 1 illustrates examples of low and high loads.

The nature of processing refers to the amount of attention required to process each unit (Lavie & Tsal, 1994). Searches for a feature-present target among feature-absent distractors require less effort and can be performed in parallel (Treisman & Gelade, 1980), resulting in a lower load on the attentional system and a greater likelihood that irrelevant information will be processed. For example, as shown in Figure 1d, the target, “N” is a distinct feature-present target among the non-target feature-absent “O’s” by virtue of its angular straight lines. However, when targets and distractors are perceptually more similar, searches require more effort and must be performed serially (Treisman, 1998), resulting in a higher load on the attentional system and a smaller likelihood that irrelevant information will be processed (Lavie & Cox, 1997). For example, as shown in Figure 1c, both the target “N” and the non-target letters (W, V, T, Y, and H) are similar in their physical appearance.

Lavie (1995) further argued that if the perceptual load created by task-relevant information is not large enough to require all of an individual’s available attentional capacity, all stimuli are processed automatically regardless of their task relevance, until capacity is exhausted (Lavie, 1995). Here, perception occurs automatically not in the

sense that it does not require attentional resources, but that it is not under voluntary or deliberate control (Lavie & Cox, 1997). Thus, a clear physical distinction between objects is not sufficient to prevent irrelevant processing. Rather, a physical feature (e.g. color, location, size, or a combination of attributes) will aid in the selection of relevant over irrelevant information, but in and of itself cannot prevent perceptual processing as long as spare attentional capacity remains (Lavie & Tsal, 1994). Under these low-load circumstances, attentional selection occurs in the later stages of information processing on the basis of semantic identity, and results in marked interference effects from irrelevant distractors. Selection occurs early, however, if the attentional capacity of the system is exhausted by task-relevant information (Lavie, 1995). Distracting task-irrelevant information is never processed, and the distractor's potential interference is smaller. According to this model, it is impossible to allocate more or less than the available attentional capacity to a display (Lavie & Tsal, 1994).

For example, Figures 1b and 1d are representative of low attentional load conditions. Under such conditions, because the available capacity has not been exhausted, people experience greater interference from incompatible distractors because they must process the entire display. Thus, the reaction time difference between incompatible and neutral distractors is large. On the other hand, Figures 1a and 1c represent high attentional load conditions. Under these conditions, people are able to ignore the distractor more effectively because the perceptual load is greater, reducing available attentional capacity. Because the peripheral distractor is not selected for further processing, its effect is smaller and the reaction time difference between incompatible and neutral distractors is small.

Critique of the Perceptual Load Paradigm

The flanker task is a common paradigm for studying selective attention, regardless of model, and will be discussed briefly here in order to further elucidate Lavie's theory. In studies using the flanker task, participants make a forced-choice response to one of two target letters while ignoring distractor letters (known as flankers) (Miller, 1991) as illustrated in Figure 2. The flankers are positioned to the right and left of the display area and are either compatible or incompatible with the response. When the distractor letters are incompatible, response times are typically slower than when they are compatible. This phenomena, termed the flanker compatibility effect (FCE), suggests that early selective attention is imperfect, and that it allows distractors to be processed to some degree, even when it is detrimental to performance.

In order to determine which conditions were necessary to maximize early selection, Miller (1991) manipulated experimental conditions in an attempt to remove the FCE entirely. In support of Lavie's (1995) model, Miller found that larger display sizes (sets of four or eight letters, as opposed to sets of two letters) resulted in a decrease in the FCE (See Figure 3). That is, the larger display sizes presumably placed greater loads on attentional capacity than smaller display sizes, and initiated early selection. As a result, response times to target detection were faster to larger as opposed to smaller displays.

However, Miller (1991) noted that the flankers could activate a response, but due to the large number of items in the display, the activation dissipated by the time participants finished searching the interior circle display. Thus, in two further experiments, Miller (1991) increased the number of targets in the displays, and delayed the onset of the flankers, both in order to better equate target and flanker recognition

times. That is, an increased number of targets would reduce the time to target detection and ensure that target searches terminate while flanker activation was still strong. Likewise, delaying flanker onset would prevent the decay of flanker activation during target search.

By making these two manipulations, Miller (1991) caused the FCE to re-emerge, even with large displays, suggesting that the number of items in the display was not responsible for early selective attention. Thus, the initial reduction in the FCE in larger displays appeared to be related more to dissipation over time of the FCE than to the display size per se. These results appeared to challenge Lavie's (1995) hypothesis.

However, other studies using flankers which were identical to the target found that they still interfered with rather than facilitated performance, possibly due to early feature-specific inhibition (Lavie, 1995). Furthermore, the effects of delaying the flanker onset is confounded with its sudden appearance. Abrupt onset or offset of objects in the visual field is known to automatically capture attention (Yantis & Jonides, 1984). The manipulation by Miller (1991) might have provided the flanker with additional salience. In all, given the confounds associated with these manipulations, Miller's (1991) results are inconclusive in their support of Lavie's (1995) model.

Nonetheless, Lavie's model has sufficient support that it provides an appealing approach to the study of selective attention. However, it has not been established that the model is applicable to children. If it is, then the model would have important ramifications for clinical studies of children. The advantages of this model for studies of selective attention are that it allows for an integration of the early and late selection approaches, and is able to integrate the apparently contradictory views of these two

opposing camps. Furthermore, the recognition that the stage at which selection occurs depends upon perceptual load is potentially critical in evaluating prior selective attention studies of childhood ADHD.

In the following review, the term “early selective attention,” refers to the selection processes which respond to perceptual features and which lead to the filtering of information prior to semantic encoding. The term “late selective attention” refers to those processes which respond to semantic features and which leads to the filtering of information only after substantial processing has already been completed.

Inattention in ADHD

Although behavioral symptoms of inattention are characteristic of both ADD+H and ADD-H children, ADD-H children are more often described as daydreamy, lethargic, confused, and lost in thought (Barkley, 1997b). Thus, the ADD-H subtype might exhibit greater early and/or late selective attention deficits than children with ADD+H, or children without ADHD. Whereas an early and/or late selective attention deficit is an unknown for ADD-H, the field remains in open disagreement about the existence of these deficits in ADD+H (Douglas, 1999; van der Meere, 1996).

From the point of view of Lavie’s (1995) model, children with either subtype of ADHD may be unable to move their selective attention from “late” to “early,” in order to filter incoming stimuli from the environment, or may require a greater perceptual load from their environment. Thus, the “beneficial” effects of high attentional load in protecting against distractor effects may be less evident in children with attentional problems. If children with ADHD are less responsive to the effects of high load, then paradoxically, they may have a greater attentional capacity than non-ADHD children.

Greater attentional capacity does not imply, however, greater efficiency in processing. On the contrary, the symptoms children with ADHD exhibit would suggest that the “additional” capacity handicaps their ability to select relevant over irrelevant information.

The idea of a wider spread of attention in ADHD has captivated ADHD theorists for some time, and the suggestion that children with ADHD are less able to adjust their attentional breadth is not new (see Zentall & Zentall, 1983). The perceptual load paradigm could provide a fresh and useful test of this idea. That is, if children’s locus of selection, like adults, shifts from late to early for low and high loads, respectively, and if the mechanisms which adjust the breadth of attention are dysfunctional in ADHD, then performance decrements would be evident under higher, but not lower, load conditions.

To evaluate this argument, I first review previous studies suggesting that children with ADHD require greater perceptual load from their environments in order to shift from late to early selection. Second, I examine a study of attentional capacity in children with ADHD. I then review a number of early selective attention studies in ADHD, followed by a review of late selective attention studies in ADHD. In reviewing the studies of early selective attention in ADHD, the criteria for optimal task design, based upon the perceptual load model, are: (1) inclusion of sufficient (i.e. high) load to allow early selective attention to be observed and (2) the presence of a competing distractor to provide incentive for attention to be focused.

ADHD and perceptual load. The proposal that children with ADHD require greater stimulation from their environments in order to maximize their selective attentional processes engages a long standing debate in the ADHD literature. Early therapeutic interventions included placing ADHD children in stimulus-reduced

environments (Ceci & Tishman, 1984), but such environments did not improve academic performance for children with ADHD (Douglas, 1983; Steinkamp, 1980). Instead, some studies reported increases in activity level when children were deprived of normal environmental stimulation (Douglas, 1983).

For example, in an early study, the addition of irrelevant peripheral visual stimuli (i.e. flashing, multicolored lights) actually reduced the number of trials minimally brain-damaged children (an early term for ADHD) in the first through fourth grade required to reach criterion on a learning task (Browning, 1967). Similarly, Ceci and Tishman (1984) found that recognition memory for visual stimuli was greater for ADHD than non-ADHD children. Children were presented with a set of pictures of everyday items and animals and told to remember each one. They were then asked to recognize the original picture from a set of pictures that included the original among pictures with missing features. For example, if the original picture was a bird with a worm in its mouth and a sun in the background, ADHD children were better able to use the non-central features of the stimuli (e.g. worm and sun) to correctly discriminate the original stimuli from distractors that had missing features (e.g. picture of a bird without a worm). Thus, children with ADHD encoded more non-central details of the visual stimuli than non-ADHD children, in an apparent demonstration of a “wider” attentional span (Ceci & Tishman, 1984).

Children with ADHD do not always perform better under distracting conditions, however. For example, they had normal recall for central pictures when the presented cards contained no irrelevant peripheral pictures, but had recall difficulties when peripheral pictures were present (Tarnowski, Prinz, & Nay, 1986). That is, ADHD children were distracted by the peripheral pictures, resulting in poorer recall of the central

stimuli. Likewise, Radosh and Gittelman (1981) found that when mathematics problems were surrounded by “no appeal,” (white) “low appeal,” (shapes) or “high appeal,” (pictures of space craft, toys, animals, etc.) borders, children with ADHD performed worse overall, but particularly badly under the high appeal condition, in comparison to non-ADHD children. These results were interpreted as evidence for a selective attention deficit in ADHD. At the least, the results did not suggest that children with ADHD benefit from greater environmental stimulation. However, children with ADHD also often have comorbid learning disabilities, and these results may have been due to lower achievement and IQ in the ADHD group, which were not controlled. Regardless, clarification of the impact of perceptual load on attention in ADHD is needed.

Whereas extra-task distractions (such as the blinking lights or white noise; distractors that are unrelated to the task at hand) have predominantly (but not always) been found to either not affect or benefit performance, intra-task or within-task distractions (such as the distractors employed in the Lavie paradigm) have been theorized to have a negative impact because they compete with the primary task for response (Barkley, 1997b). The point will be returned to in relation to late selective attention and interference control.

ADHD and attentional capacity. That children with ADHD sometimes perform better under distracting conditions suggests that they might possess a greater attentional capacity than non-ADHD children. Attentional capacity in ADHD subtypes has not been studied directly. However, Schachar and Logan (1990) used a dual task paradigm to compare capacity between children with and without DSM-III-R ADHD. The capacity-sharing models of dual task paradigms propose that a greater temporal overlap between

the primary and secondary tasks causes the tasks to compete for attentional resources. If adequate resources exist, then the advent of the second task should have no adverse effects on the performance of the primary task. Schachar and Logan (1990) predicted that children with ADHD have less attentional capacity than control children and would be more adversely affected by greater temporal overlap between the primary and secondary tasks. This was not the case, however. Although children with ADHD were slower to respond on both the primary and secondary tasks, there was no significant interaction between groups as temporal overlap increased. The results were therefore interpreted as indicating no ADHD deficit or advantage in attentional capacity.

However, an alternative interpretation of the dual task paradigm can be supported. Poor performance in dual task paradigms may not reflect sharing of attentional capacity, but rather a central processing bottleneck (Pashler, 1994). If attentional capacity was being shared, and if the children were instructed to attribute equal importance to both the primary and secondary tasks, then when onsets of both tasks were simultaneous, the reaction times to both should have been approximately equal in the Schachar and Logan (1990) task. However, the children were told to prioritize the primary task. This instruction created a pattern of performance more consistent with a central processing bottleneck than with the shared attentional capacity model. The central processing bottleneck theory proposes that parallel processing is impossible for certain mental operations. If two such tasks require the same mechanism at the same time, one task is necessarily delayed or impaired (Pashler, 1994). In terms of performance, this translates as faster reaction times in the primary task, and slower reaction times in the secondary task—the pattern of results observed by Schachar and Logan (1990). Thus, it is not clear

that attention was shared in their dual task design. As a result, the interpretation of normal attentional capacity in ADHD remains open to question.

ADHD and early selective attention. Despite the inattentive behavioral symptoms of children with ADHD, previous research has not consistently supported an early selective attention deficit in the combined subtype of ADHD (Douglas, 1983; Taylor, Sandberg, Thorley & Giles, 1991). When re-interpreted using Lavie's model of selective attention, however, these negative findings may be due to task designs which were not optimized to study early selective attention. In addition, most did not distinguish between ADHD subtypes. And finally, many studies used very small samples with low power. As stated previously, in reviewing studies of selective attention, the criteria for an optimal task design, based upon Lavie's model of selective attention, are as follows: (1) the inclusion of sufficient load to allow early selective attention to be observed, and (2) the presence of a competing distractor which must be suppressed for accurate performance. That is, if the load is insufficient, group differences on early selective attention processes would not be observed because early selection could not occur. A competing distractor creates a cost to performance if it is processed, and thus requires participants to focus their attention to perform well. If it is absent, participants do not need to focus their attention.

With regards to the inclusion of sufficient load, van der Meere and Sergeant (1988) asked 12 ADHD and 12 non-ADHD children between the ages of 8-10 to determine whether a target letter was located along one diagonal of a rectangle. In some trials, a target letter foil also appeared on the opposite diagonal (which, in order to provide the most efficient performance, had to be ignored). All children showed a

slowing of reaction time when the target foil was present, but there was no significant group x trial type interaction. Thus, van der Meere and Sergeant (1988) reasoned that children with ADHD did not possess a selective attention deficit. de Sonneville, Njokiktjien, & Hilhorst (1991) using the same task, replicated van der Meere and Sergeant's (1988) results, but also found that error rates during the distraction conditions did not improve following administration of methylphenidate. Barkley, Anastopoulos, Guevremont, and Fletcher (1991) found that adolescents with ADHD ($n = 84$), committed more errors of commission, but not of omission, than controls ($n = 77$) on a version of the CPT task in which distracting numbers were flashed either to the right or left of the target (a "1" followed by a "9"), but the differences were not significant.

In each of the preceding studies, although competing distractors were present, a maximum of three perceptual units per trial were present. These would be considered "low load" conditions (at least for adults) in Lavie's model. As will be recalled, low load is associated with late selection of internal representations based upon task demands. Under these conditions, neither the control nor the ADHD children would be expected to produce evidence of early perceptual selection, according to Lavie's model. In adults, Lavie (1995) was able to observe early selection only when six perceptual units were displayed. The lack of an interaction between ADHD and control children in the preceding studies may therefore be due to the fact that neither group was able to perceptually select out and thus prevent processing of the irrelevant stimuli. Indeed, van der Meere and Sergeant (1988) found a significant main effect of the distractor condition, suggesting that even control children were unable to effectively filter the distractor in this low load (late selection) task. Rather, results of this study may suggest that children with

ADHD do not demonstrate deficits in interference control, discussed later. In order to determine whether ADHD children possess a deficit in early selective attention as defined by Lavie, it would have been necessary to include higher load conditions.

Other studies provided higher perceptual loads but did not provide competing irrelevant information that must be suppressed. McIntyre, Blackwell, and Denton (1978), asked children aged 6-10 with ($n = 19$) and without ($n = 19$) ADHD to vocally report the presence of a target letter (either “T” or “F”) embedded in a 4 x 4 letter array composed of: 1) all O’s, 2) all U’s, 3) all I’s, 4) all E’s, 5) O’s and U’s, and 6) I’s and E’s. McIntyre et al. (1978) reasoned that if children with ADHD possessed a central deficit in the extraction, analysis, and encoding of external information, then they would commit more errors than controls under conditions in which the letter array was either (1) physically dissimilar to the targets (i.e. O’s or U’s), or (2) was redundant (i.e. composed of all the same letters). That is, control, but not ADHD children, would be expected to take advantage of these conditions to increase the efficiency (as measured by error rates) of their visual search. Although McIntyre et al. (1978) found a main effect for noise condition, and ADHD children made more identification errors overall, there was no significant group x condition interaction. This finding suggested that the noise letters (i.e., E and I) affected central search processes for ADHD and control children to an equivalent degree. Described another way, both ADHD and non-ADHD children were able to utilize the physical dissimilarity of distractors and the redundancy of the letter array to improve their performance.

However, if selective attention is defined as the ability to attend to one piece of external information while ignoring others, the task McIntyre et al. (1978) used was not

adequate. That is, determining whether the target was a “T” or an “F” required that all the letters in the stimulus array be attended and encoded in all conditions. Although the display size of 16 was adequate for a high load, according to Lavie’s model, there were no irrelevant distractors. Good performance on a test of early selective attention should require participants to ignore irrelevant and competing aspects of the stimulus field. Thus, an alternative explanation of McIntyre et al.’s (1978) results is that children with ADHD possess normal active (as opposed to automatic) visual-spatial *search processes*, or spatial attention. This would be a rather different process than *early selective attentional* abilities, as defined herein.

Sharma, Halperin, Newcorn, & Wolf (1991) asked 73 non-referred school children with a mean age and (sd) of 9.5 (1.8) to respond to the appearance of a central blue square (but not to the appearance of a red or yellow square) in the presence of 0, 2, or 5 smaller green distractor squares appearing in the periphery. Although performance on the focused attention test was significantly correlated with performance on a continuous performance test (CPT), it was not related to teacher measures of inattention or conduct problems, and only mildly related to hyperactivity (Sharma et al., 1991). Based on their performance (reaction time) on the focused attention task, children were then divided into three groups: underfocused (n = 6), normofocused (n = 38), and hyperfocused (n = 5). Underfocused children had slower reaction times (> 1 SD above the mean), and hyperfocused children had faster reaction times (>1 SD below the mean), in the 2 and 5 distractor condition. Normofocused children performance fell between the 25th and 75th percentiles. Children falling in between these groups were excluded to provide clear group distinctions. Both underfocused and overfocused children were rated

as more hyperactive by their teachers than normofocused children. The authors suggested that hyperactive children may be deviant in their ability to focus attention which may be under or overfocused (Sharma et al., 1991).

However, a clearer interpretation regarding early selective attention in hyperactive children in the latter study is difficult. Although the task had conditions of low load (0 and 2 distractor squares) and higher load (5 distractor squares), the task did not include a true competing distractor. That is, in order to effectively measure early selective attention (or even late selection for that matter), small blue square(s) rather than only green squares, would have to have been included among the peripheral distractors so the children's ability to ignore the presence of *peripheral* blue square distractors, while searching for the *central* blue-square target, could be measured. The distractor must not only be present and irrelevant, but also competing (i.e. similar to the target) to challenge the attentional selection system as defined by Lavie (1995).

Interestingly, when a target differs from distractors on the basis of one distinctive feature such as color, automatic, parallel search processes typically take place so that reaction time is independent of set size (Treisman & Gelade, 1980). This was not observed by Sharma et al. (1991). Instead, steady increases in reaction time were observed as the number of distractors increased, suggesting that all children, regardless of group, were initiating a serial search process. Unlike the McIntyre (1978) findings, the Sharma et al. (1991) results may suggest that hyperactive children do have deficits in effortful, serial search processes. However, these results do not speak as strongly to the question of selective attention in ADHD.

Zentall, Zentall, and Barack (1978) also attempted to determine whether extra-

task distraction would be greater for ADHD ($n = 25$) than control ($n = 22$) children aged 6 to 10. They measured children's performance on two paper and pencil copying tasks, a block design task, and a rapid naming task. The distractor manipulation was to present each of the tests in color rather than in black and white. Although children with ADHD made more errors and were more impulsive in their responses overall, a group $\times$ color condition interaction, in which children with ADHD performed more poorly, was found only for one of the copying tasks and for repetition errors (i.e. naming a shape that had already been named) on the rapid naming task (Zentall et al., 1978). Although this study is sometimes cited as providing evidence for a selective attention deficit (van der Meere, 1996), the study itself was designed to determine whether ADHD children would benefit from additional, non-competing within-task stimulation in order to test an optimal arousal theory (see Arousal section). Again, the experimental manipulation (in this case, added color) does not compete with task performance and therefore is not optimized to test for selective attention as defined in Lavie's (1995) model. Furthermore, changing the color of the entire stimulus is unlikely to change the perceptual load of the display.

In a speeded classification study, controls ($n = 13$), children with ADHD ($n = 14$), ADHD + LD (reading disability) ($n = 12$), and LD alone ($n = 12$) were asked to sort cards on the basis of either: form (circle/square), line orientation (horizontal/vertical), or star position (high/low) (Tarnowski et al., 1986). The cards had either zero, one, or two irrelevant dimensions in addition to the relevant dimension by which children were being asked to sort. Both the LD and ADHD + LD groups, but not pure ADHD or controls, displayed significantly slower card sorting times in the presence of irrelevant dimensions, suggesting that the selective attention deficit was confined to LD only (Tarnowski et al.,

1986). This finding is potentially important given that other studies failed to control for LD. However, once again, the card sorting task did not provide a competing distractor and thus was not an optimal design to test for selective attention as defined by Lavie (1995). Using a similar card-sorting task, Hooks, Milich, and Lorch (1994) found that whereas ADHD boys ($n = 40$) were significantly slower than controls ($n = 52$), there was no group x irrelevant dimension interaction, suggesting that ADHD boys were no more distracted by the irrelevant information than controls. However, because 4 or more errors in the card sorting task (3 or more, for Tarnowski et al. (1986)) led to re-administration, if children with ADHD did make more errors due to deficits in selective attention, the effect would have been removed entirely. Furthermore, the additional practice through the re-administration of the task for children performing poorly would be expected to diminish any group effects or interactions which might otherwise be observed.

Lavie's (1995) theory of selective attention refers specifically to visual stimuli, so evaluations of selective attention tasks and interpretations using her model in the auditory modality are less clear-cut and are not central to the current study and review. However, the possibility of an auditory selective attention deficit in ADHD is supported by evidence that children with ADHD perform poorly in dichotic listening tasks (Dalebout, Nelson, Hletko, & Frentheway, 1991). Furthermore, children with ADHD did not display the normal ERP responses to auditory attended stimuli, and only partially to visual stimuli, suggesting deficits in auditory and visual selective attention (Satterfield, Schell, & Nicholas, 1994). Negative evidence also exists, however. Davidson and Prior (1978) found that both ADHD ($n = 20$) and non-ADHD ($n = 20$) children demonstrated a normal right-ear advantage during a dichotic listening task and no group differences in selecting

relevant over irrelevant material.

In summary, although empirical evidence regarding an early selective attention deficit has been contradictory, some evidence for such a deficit does exist. Most studies used tasks lacking either sufficient load and/or the presence of competing distractors, rendering a clear conclusion on the matter difficult. Low power in many studies, a lack of ADHD subtyping, and rare control of comorbidity also limit the earlier literature. Thus, whether children with the combined subtype of ADHD do or do not have an early selective attention deficit remains inconclusive on a number of grounds, and deserves further study. On the other hand, early selective attention has hardly been examined at all in the recently redefined inattentive subtype. Given the latter group's defining symptomology of inattention, such an examination is long overdue.

However, it is important to note that early selective attention processes do not take place in isolation. Rather, early selective attention is associated with other processes including Late selective attention and arousal, and their consideration will be needed to fully interpret the selective attention results for the current experiments. The two key processes to be discussed are interference control and arousal.

Late Selective Attention

Late selective attention is similar to what others have referred to as interference control, defined as the suppression of distractors to protect performance on a primary task (Dempster, 1993; Nigg, 2000). For the purposes of this essay, the term late selective attention will be used throughout. As stated previously, early selection based upon the external perceptual environment is a distinctly different process than the late selection of mental representations based upon task demands. Because behavioral symptoms of

inattention in DSM-IV ADHD do not discriminate between these two processes, including as descriptors distraction to both external and internal stimuli, it is necessary to determine whether the inattention reflects an early selective attention deficit to external stimuli, or a late selective attention/interference control deficit. Making a distinction between these two selective processes is particularly important with regards to defining the cognitive deficit profile of ADHD subtypes.

ADHD and late selective attention. The proposition that children with ADHD possess a dysfunctional inhibitory system of some type has existed from the earliest conceptualizations of the disorder. However, recent research has not supported a unitary construct of inhibition based upon a single anatomical structure. It is not surprising, then, to find that some, but not all inhibitory processes, are problematic in ADHD (Nigg, 2001). Positive evidence for an interference control deficit for children with ADHD, as measured by the Stroop task, has been mixed (Barkley, 1992; Carter, Krener, Chaderjian, Northcutt, & Wolfe, 1995; Houghton et al., 1999; for review see Nigg, 2001). Many of these studies did not control for overall slower naming speeds in ADHD, but the balance of results from Stroop studies suggest that children with ADHD do not exhibit increased disruption from irrelevant and incongruent stimuli when the stimuli activate a competing automatized response, although adolescents may (Nigg, 2001).

However, when tested with a version of the Eriksen flanker task, ADHD children not only made significantly more errors than controls, but made specifically more errors to incongruent vs. neutral distractors, than controls (Jonkman et al., 1999). Because ADHD children's performance was similar in the target alone and neutral distractor conditions, the authors suggested that the deficit was one of response preparation, as

opposed to perceptual interference. That is, ADHD children did not display a deficit in “early” perceptual selection for elementary stimulus attributes, but rather a “late” response selection deficit (Jonkman et al., 1999). Presenting stimuli in a trial-by-trial format as in the Jonkman et al. (1999) study may explain the difference for the positive findings for a late selection deficit in flanker task as opposed to the majority of studies of ADHD on the Stroop task which did not use this format for stimulus presentation. But, whether Jonkman et al. (1991) would have found the same pattern of results in ADD-H children as they did for ADD+H children, or whether ADD+H children’s performance to incongruent stimuli would have improved under conditions of higher perceptual load, is unknown. Extensive neurochemical and physiological evidence also supports a deficit in frontal networks related to inhibitory control and interference control in the ADHD combined subtype. That evidence is summarized further in Appendix I.

Aside from two studies of Stroop performance in adolescents with ADHD, and one study using trial-by-trial presentation of stimuli (in the Jonkman et al. (1999)), it has proven difficult to isolate an interference control deficit in children with ADHD (Nigg, 2001). Re-examination using a late selection flanker paradigm is therefore needed.

ADHD and response modulation. In direct opposition to the results discussed in the previous section, Newman (1998) argues that a process known as response modulation is deficient in individuals with behavioral regulation disorders (e.g. psychopaths), and that this process may be relevant to children with ADHD as well. According to this model, psychopaths do not effectively engage in the automatic attentional monitoring of peripheral information, and they therefore demonstrate less interference from peripheral distractors than non-affected individuals (Newman, 1998).

The response modulation theory is based upon Gray's (1987) model of septo-hippocampal functioning which includes a behavioral inhibition system (BIS), behavior activation system (BAS), and a nonspecific arousal system (NAS). Gray (1987) postulated that the BIS is activated by cues for punishment. Once activated, the BIS increases NAS activity and interrupts goal-directed behavior. The individual is then able to re-evaluate the continued appropriateness of the goal-directed behavior. On the other hand, the BAS is activated by cues for reward (Gray, 1987). The activated BAS then increases NAS activity and decreases BIS activity, allowing approach behaviors to proceed. Disruptions in either the BIS or the BAS systems may cause deficits in the self-regulation of behavior according to Gray's (1987) theory (Newman & Wallace, 1993). That is, a person may either be hypersensitive or excessively activated by reward, or if they are excessively sensitive to punishment, they may behave with "anxious impulsivity." Studies of psychopaths and externalizing behavior disorders have utilized this and other related theories to explain psychopaths' reduced sensitivity to punishment cues (Newman, 1998).

However, disruptions in the response modulation process that Newman and colleagues have described could also lead to deficits in self-regulation (Newman & Wallace, 1993b). Unlike non-affected individuals, psychopaths' automatic monitoring of peripheral cues is more effortful, and they therefore have more difficulty arresting their primary goal-directed behavior to evaluate new feedback cues. Newman (1998) not only argued that psychopaths less responsive to negative feedback, as the BIS/BAS theory would predict, but also that they are less responsive to neutral peripheral cues (Newman, Schmitt, & Voss, 1997). Thus, when presented with situational motivations to misbehave,

psychopaths are more apt to do so, because they are not as able to monitor and evaluate feedback cues against such behavior.

Newman and colleagues have speculated that response modulation deficits may also contribute to the development of ADHD (Newman & Wallace, 1993b). Difficulties with behavioral regulation are often observed in children with ADHD, particularly under situational factors such as boredom, frustration, and opportunities for immediate gratification which require self-regulation (Newman & Wallace, 1993b). The comparison between psychopaths and children with ADHD is better for children with comorbid conduct disorder as opposed to ADHD alone. However, Newman and Wallace (1993b) contend that their metaphor refers specifically to the processes which may be involved in deficits in self-regulation, as opposed to the specific behaviors themselves. In contrast to predictions based on a late selective attention deficit, this model would predict “better than normal” selection by children with ADHD due to diminished detection of peripheral cues.

Selective Attention and Response Modulation in Relation to the Perceptual Load Model

According to the perceptual load model, children with ADHD could have a deficit in early perceptual selection, which results in the encoding of large amounts of extraneous, and ultimately distracting, stimuli. In comparison to non-ADHD children, their performance would be worse at high loads. On the other hand, the “inattention” could also be due to deficits in late selection, or interference control. If so, they would perform more poorly than controls at low loads where interference control would be necessary. It is not clear whether the automatic monitoring and response modulation processes described by Newman and colleagues is identical to the selective attentional

processes that have been described here. But, if one were to accept the response modulation hypothesis, then one would expect children with ADHD to demonstrate less interference than controls at smaller set sizes, because children with ADHD are less able than controls to automatically monitor peripheral information and therefore to be distracted by it. More discussion of a model for distinguishing the ADHD subtypes in terms of early selective attention, late selective attention, and response modulation is provided later.

The third major cognitive system relevant to interpreting the proposed study, arousal, will now be discussed in relation to both ADHD as well as to early and late selective attention.

Arousal and State Regulation

Arousal is often conceptualized as a unitary construct used to describe an intensive dimension of behavioral activation from low (e.g. sleeping) to high (e.g. stress) (Proctor & Dutta, 1995). It is believed to be largely controlled by subcortical structures, particularly the reticular activating system (RAS), although the right cortical hemisphere has also been implicated as a mediator of arousal (Heilman & Van Den Abell, 1979; Posner & Peterson, 1990). Neurochemically, norepinephrine (NE) plays an important role in arousal processes. There are two major NE pathways in the brain: the dorsal and ventral bundles. The dorsal pathway originates primarily from the locus coeruleus (LC) and projects rostrally to the medial forebrain bundle and to the limbic system (Solanto, 1998). The ventral pathway originates in the rostral medulla oblongata and projects to the hypothalamic and peri-hypothalamic areas (Solanto, 1998).

NE is released in situations which require the rapid allocation of attention and it

aids performance by increasing signal-to-noise ratios (Servan-Schreiber & Cohen, 1992; Solanto, 1998). Noradrenergic projections also extend throughout the cortex, with large concentrations in the prefrontal cortex, thus making NE potentially important in working memory and to late selection processes which utilize the prefrontal cortex (Solanto, 1998). High tonic levels of LC activation are associated with hyperarousal, agitation, as well as increased errors of commission and omission. Low levels of activation are associated with drowsiness, poor performance, and errors of commission (Solanto, 1998).

Yerkes and Dodson, in the early twentieth century, were the first to conduct a series of experiments correlating level of arousal to performance (Proctor & Dutta, 1995). The two main principles to arise from this work were that: 1) performance fell along an inverted U-shape, with optimal performance occurring at some intermediate level of arousal, and 2) optimal arousal levels are higher for simple tasks, and lower for complex tasks (Proctor & Dutta, 1995). Although accounts and explanations of the Yerkes-Dodson curve vary, it is generally accepted that arousal affects performance indirectly by altering information processing (Proctor & Dutta, 1995).

The Cue Utilization hypothesis is often used to describe the Yerkes-Dodson curve. It states that the number of perceptual cues to which a person can observe, orient, or respond at any one time is a function of the level of arousal (Eysenck, 1982; Proctor & Dutta, 1995). Very high states of arousal restrict, and very low states of arousal increase, this capacity (Proctor & Dutta, 1995). Thus, as arousal increases, the number of task-irrelevant cues available for processing is reduced, ultimately aiding performance. However, if arousal continues to climb, even task-relevant cues are increasingly excluded, leading to deficits in performance. This account of performance bears some

resemblance to Lavie's selective attention theory, in which a greater perceptual load diminishes attentional capacity. She makes no predictions regarding the influence of arousal on selective attention or how perceptual load may affect states of arousal, however.

Experimentally, performance which deteriorates more quickly *over time* than a comparison sample is believed to reflect deficits in sustained attention (often referred to as vigilance) (Parasuraman, Warm, & See, 1998; Halperin, 1991). In contrast, poor performance at the *outset of a task*, which decreases at the same rate as a comparison sample, is believed to reflect deficits in arousal (Parasuraman et al., 1998; van der Meere, Wekking, & Sergeant, 1991) (See Figure 4). Slow and variable reaction time is a typical index used to define poor performance due to inadequate task-specific arousal.

Direct evidence that slow and variable reaction time performance is related to levels of arousal were found in an experiment in which arousal levels were pharmacologically manipulated in normal adults by the administration of placebo, methylphenidate, or diphenhydramine, an antihistamine (Oken, Kishiyama, & Salinsky, 1995). Participants were then tested with an endogenously cued covert orienting task and a visual search task. Levels of arousal were measured by EEG analysis and subject self report on the Stanford Sleepiness Scale. Reaction times on both attention measures were slowest and most variable under diphenhydramine. The fastest and least variable reaction times occurred following administration of methylphenidate. EEG readings and self report measures corroborated changes in cortical arousal levels following administration of methylphenidate and diphenhydramine in the expected directions. According to Posner and Peterson's (1990) model of attention, the sustained attention/vigilance system is

based in part on the RAS, the same system believed to be involved with arousal.

However, because dissociations in performance deficits do occur, it is unlikely that sustained attention/vigilance and arousal are one and the same.

ADHD and arousal

The hypothesis that children with ADHD suffer from a deficit in arousal is not new. On the other hand, how arousal has been conceptualized, and how the arousal deficit in ADHD has been described, has long been debated.

One theory proposes that children with ADHD are hyperactive because they are chronically hyperaroused by an “overflow” of stimuli (Zentall & Zentall, 1983). The Optimal Stimulation Theory, on the other hand, proposes that each child has a biologically determined optimal level of stimulation (Zentall & Zentall, 1983). Thus, an individual will increase stimulation-seeking activity when such stimulation is insufficient for optimal performance, and will withdraw from activity when the stimuli is too great.

According to this model, children with ADHD, much like extreme extroverts (Geen, 1984), are chronically hypoaroused and their hyperactivity is viewed as an attempt to increase arousal levels (Zentall & Zentall, 1983). Thus, a deficit in arousal would result in an inability to maintain a wakeful state if prevented from fidgeting, moving, or daydreaming during continuous mental processing (Weinberg & Harper, 1993). When body movements (i.e. auto-manipulations, arm movements, trunk movements, body shifts, and leg movements) were coded during the execution of a version of the CPT task, children with ADHD made significantly more body movements, which increased significantly with time on task (Alberts & van der Meere, 1992). Overall performance on the CPT did not differ between groups, however, leading the authors to suggest that

perhaps children were making such movements in order to maximize their arousal levels which thus prevented declines in task performance (Alberts & van der Meere, 1992).

Patterns of reaction and error performance on the CPT and other reaction time measures have supported an arousal deficit in the ADHD combined subtype (van der Meere, Wekking, & Sergeant, 1991). That is, from the outset, children with ADHD are slower, commit more errors, and are more variable in their performance than controls, but their performance does not worsen over time to a greater degree than controls. This pattern has consistently been found across experimental conditions and across tasks requiring rapid response, and may be seen as an important established finding for ADHD in and of itself (Douglas, 1999). Sergeant et al. (1999) argued that this pattern of performance could well represent deficits in activation (the physiological readiness to make a response), or effort (the energy required to meet task demands), rather than hypoarousal. They refer to state regulation to encompass possible patterns in arousal, activation, or effort. However, for the purposes of this paper, slow, inaccurate, and highly variable performance which does not decrease over time is interpreted as an arousal deficit.

Douglas (1999) pointed out that closer examination of distributions of reaction time data often reveal a positive skew towards slower responding by children with ADHD, suggesting that group differences found between ADHD and controls are due not to an overall pattern of slow and variable performance, but rather to a disproportionately larger number of slower responses in the ADHD group. She noted that when performance on warned reaction timed tasks is compared between ADHD, normal, and younger controls, ADHD children are slower and more variable than younger controls, who are in

turn slower and more variable than normal controls. Because ADHD children performed worse than their younger non-ADHD counterparts, it is unlikely that this pattern in ADHD is merely the result of delayed maturation. Instead, it is more likely that the slower and more variable performance is due to an inability to consistently allocate their attention to the task (Douglas, 1999), as would be expected if they were unable to maintain optimal levels of arousal. Likewise, when tested in a dual-task paradigm, in comparison to controls, children with ADHD were more variable in their performance of the primary task once the secondary task was introduced, and this variability was affected by the degree of temporal overlap between the two tasks (Schachar & Logan, 1990). That is, children with ADHD were unable to consistently protect their performance on the primary task from secondary task interference, and thus traded speed on the primary task for speed on the secondary task much more often than non-ADHD children. Positive evidence for an arousal disorder is more extensive for the combined subtype, and while less is known about arousal functioning in the inattentive subtype, it is plausible that children with ADD-H also have an arousal deficit.

Extensive research on the neurochemical and physiological evidence of an arousal deficit in ADHD is summarized in Appendix II. In summary, if hypoarousal is indeed a feature of ADHD, then their symptomatic inattention or disinhibition may be due to or be moderated by deficits within the arousal system. Or, it may be that children with ADHD possess multiple, possibly independent, dysfunctions in arousal, attentional, and/or inhibitory systems. Under this scenario, the picture would be clarified if we knew whether children with ADD+H or ADD-H have dysfunctional early (perceptual) selective and/or later (interference control) selective attentional processes.

Summary

The overarching aim of the proposed research is to clarify early and late selective attention functioning in the combined and primarily inattentive subtypes of childhood ADHD. Research on the role of perceptual load in selective attention has advanced understanding of selective attention in adults, making it a promising approach to re-examine attention in childhood ADHD. However, the operation and development of load-dependent selection processes in children has not previously been mapped. This is pre-requisite to a study of children with ADHD. Therefore, Lavie's (1995) paradigm was first examined in two studies of non-ADHD children to evaluate its applicability in a developmental context in children. Conceptual considerations in mapping the normal development of selective attention have not yet been discussed, and these issues are therefore addressed as the introductory material for Study 1 and 2. Having established the perceptual load model's application in children, the paradigm was then tested on children with ADD-H, ADD+H, and non-ADHD controls in Study 3.

Study 1

Existing Evidence on Development of Selective Attention

Although selective attention has been studied extensively in children using a variety of task paradigms, including the Stroop (Macleod, 1991), it has not been studied using a variable load model such as that advanced by Lavie (1995). Examination of these processes using variable loads is necessary because, as implied in the preceeding section, one cannot necessarily generalize from the processes activated in those prior studies to results that would be obtained with variable load.

For example, Enns and Girgus (1985) found when 8, 10, and 20 year old

participants were asked to make judgements on the direction of a curved line in the presence of a single distractor, the 8 and 10 year old children demonstrated greater interference from the distractor than the adults. Subsequent investigations with greater perceptual load also showed that children suffered greater interference from distractors than did adults (Enns, 1993; Enns & Akhtar, 1989). However, whether systematic increases in perceptual load moderate interference from distractors for children, as they do for adults, is unknown. Further, whether these responses are altered by children's smaller capacity is not well understood.

Thus, prior work does not directly address the question of children's performance on a variable load task. Nevertheless, established developmental principals enable some predictions to be made. First, developmental theories of cognition propose that both the capacity available for information processing, and the speed with which any given stimulus' processing is completed, become increasingly efficient throughout early development and into maturity, but regress in later life. This means that a failure of selective attention will be more costly for younger children and older adults, because the capacity and speed needed to deal with simultaneous stimuli is reduced.

Second, developmental theories of cognition have proposed that processes involved in selective attention become increasingly differentiated and efficient throughout early development and into maturity, but that they regress in later life. Hence, failures of selective attention are more likely for younger children and older adults, compounding the problems created by developmental trends in capacity and speed.

Finally, processes which consolidate earlier in childhood are generally believed to be more automated and less likely to regress in later life. On the other hand, cognitive

processes that develop later in childhood or not until adolescence tend to be more effortful and are more likely to regress in later life (Plude, Enns, & Brodeur, 1994). Thus, if the mechanisms that support early versus late selection mature at different rates, they will be differentially available to support the demands of processing environmental information, both early in development and among older adults.

Should we expect early versus late selection processes to mature at different rates? Neural maturation proceeds along a caudal to frontal gradient (Epstein, 1986) such that posterior systems of attention develop earlier than anterior systems (Posner, Rothbart, & Thomas-Thrapp, 1997). In the case of the current model, this would suggest that early selection processes, thought to depend on earlier developing posterior cortical and subcortical systems, should develop earlier in childhood and be less likely to regress later in life. Indeed, it is now known that prefrontal cortex, including some of the systems implicated in semantic selection, continue to mature throughout childhood and adolescence (Huttenlocher & Dabholkar, 1997) along with corresponding abilities in interference control (Dempster, 1993; Harnishfeger, 1995). Thus, late selection processes, thought to depend upon later developing anterior systems, should develop more slowly in childhood and regress more quickly in old age.

Regression later in life in relation to late selection processes was demonstrated by Maylor and Lavie (1998). When compared to college aged students (mean age = 22.7 years), older adults (mean age = 73 years) demonstrated significantly larger interference effects from incompatible distractors in conditions of low load (set size of 1) as compared to high load (set size of 4) (Maylor & Lavie, 1998). In addition, the magnitude of the interference effect (incompatible minus neutral reaction time) for incompatible distractors

decreased significantly from 84 ms at set size of 1 to 38 ms at a set size of 4 in the older, but not the younger, participants. For the younger participants, a similar decrease in magnitude of the interference effect also occurred, but at a larger set size (between set size 4 and set size 6). Thus, older participants appeared to exhibit evidence of “early” or perceptually-based selection, defined by reduced interference from competing distractors, at a lower perceptual load than younger adults (Maylor & Lavie, 1998). This pattern suggested that the older adults’ processing capacity was smaller than that of the younger adults, and that the older adults thus relied more on early selection and less on late selection than did the young adults.

If selective attention follows a developmental path of increasing complexity and control in early life to regression in later life, one might expect children’s performance on tasks similar to that of Lavie’s (1995) to appear similar to those of the older participants in Maylor & Lavie (1998). That is, in comparison to college-aged adults, children might be expected to exhibit (1) greater interference effects for incompatible distractors when load is low, and (2) smaller perceptual capacities, as demonstrated by the reduction of interference from the distractor at smaller set sizes, but (3) similarity to adults in their selection ability when load is high and all perceivers are relying on the developmentally less sensitive processes of early selection.

Aims and Hypotheses for Study 1

The aims of this first study were to (1) replicate Lavie’s (1995) findings in an independent sample of young adults, using procedures based on those original experiments, and (2) evaluate whether the perceptual load model was applicable to school-aged children.

Based on Lavie's already-published findings from this task, it was hypothesized that the adults would show greater interference effects at low versus high loads. It was expected that "high loads" would occur at a set size of six elements to scan. In the case of children, it was hypothesized that the same pattern of performance would hold as the adults, but with two differences. First, "high load" would occur at a smaller set size than for the adults, because children should have less attentional capacity than adults. Second, children might show adult-level performance at high load, but not at low load. For high loads, selection would be under the control of posterior-attention-system processes that are relatively developmentally insensitive, whereas for low loads, selection would be under the control of the highly developmentally sensitive anterior attention system.

In Study 1, 4th grade children (aged 9-10) were compared with college aged adults as an initial examination of developmental differences in selective attention.

Method

Participants

Young Adults. Twenty-seven undergraduates were recruited from the Department of Psychology's subject pool. Seven of the adults self-reported medical, health, psychological, or learning problems (e.g. Attention Deficit Hyperactivity Disorder (ADHD), learning disability, depression, chronic fatigue syndrome, and drug/alcohol abuse) and were removed from analyses. This left $n = 20$ (10 men and 10 women); all had normal or corrected to normal vision. Mean age (and sd) was 20.09 (0.94) years; most were successful students, with a mean Grade Point Average (and sd) of 3.05 (0.64) on a 1.0 to 4.0 scale.

Children. Forty 4th grade children, aged 9-10 with English as a first language,

were recruited from regular education classrooms at two local schools. Six children had either teacher-reported history of attentional or learning problems or spoke English as a second language; they were removed from analyses leaving a final $n = 34$ (17 boys, 17 girls). Prior to participation, parents provided written informed consent. Children provided verbal assent. Children were taken from their classroom one at a time to a private room where the selective attention task was administered. Following the completion of the task, children were given a small prize (i.e. pencil or stickers) for participating.

Procedure

These methods were based, with some modifications for administering the task to children, on Lavie's selective attention paradigm as implemented by Maylor & Lavie (1998). The experiment, lasting approximately 20 minutes, was presented on a PC computer using the MEL programming language. Most children were able to sustain effort and involvement in the task for this period of time without noticeable problems, although as noted later, quality of task participation was considered carefully prior to data analysis. All letters were presented in uppercase and were light grey in color on a black background.

A fixation point appeared for one second prior to every trial. During the trial, a target letter, either an "X" or an "N," randomly and equiprobably appeared at one of six positions in a circle located at the center of the computer screen. The display sequence is illustrated in Figure 5. Each letter display was presented for 200 ms. The use of a 200 ms display period was chosen by the following considerations. Eight to ten year old children are able to maintain verbally-instructed central gaze fixation for approximately 400 ms

following the sudden onset of a peripheral cue (Paus, Babenko, & Radil, 1990). Further, school aged children require on average between 250-300 ms to complete a saccade to a peripheral target (Munoz, Hampton, Moore, & Goldring, 1998; Ross, Hommer, Breiger, Varley, & Radant, 1994; Rothlind, Posner, & Schaughency, 1991). Thus, a 200 ms delay interval would be well within limits to preclude eye movements in the child populations given verbal instructions to maintain fixation. At the same time, as discussed subsequently, even at 200 ms, many of the younger children had difficulty perceiving the stimuli, leading to unacceptable error rates. Thus, faster presentation rates were judged not to be feasible. Identical tasks were chosen for adults and children despite a risk of eye movements in the adults. However, eye movements by the adult participants would only interfere with correct task performance, and render group differences more difficult to detect.

The task was to make a correct key press as fast as possible upon detecting the target in which the “X” key was the numeral 1 and the “N” key was the numeral 2 on a right-sided number pad. “X” and “N” stickers were placed over the appropriate numerals. Participants were asked to make the key press with the index and middle fingers of their dominant hand, but were allowed to use the index fingers of both hands if this was more comfortable, and if it would allow them to respond more rapidly. Children more often chose the two-handed option, which was easier for them due to their small hand size.

The target letter either appeared alone, or grouped with one, three, or five non-target display letters (i.e. Z, K, Y, V, or H) which randomly appeared in different positions along the circle. A larger grey irrelevant distractor letter randomly appeared either to the left or the right of the letter display (i.e. T, L, X, or N). The larger size of the

distractor was to compensate for its greater distance from the fixation point. Distractors had an equal probability of being either incompatible or neutral. An incompatible distractor was the presence of an X or N in the periphery. Because this distractor was never the same as the target letter, it would always activate an incorrect response if identified. A neutral distractor was the presence of a letter T or L in the periphery. Because these were not targets to which responses were assigned, they would not activate a response even if identified. Feedback for incorrect responses was provided by a computer tone. There was no tone on correct trials. A one second inter-trial interval followed every response.

The target and non-target letters subtended a visual angle of 0.6° vertically and 0.4° horizontally. The imaginary circle on which the target and non-target letters were placed had a radius of 2.1° from a central fixation point. The irrelevant peripheral distractor subtended a visual angle of 0.9° vertically and 0.5° horizontally and appeared to the right or left of the circle of letters at a distance of 4.3° from fixation.

The examiner read the following instructions aloud prior to beginning the task:

“In the middle of the computer screen, you will see either 1, 2, 4, or 6 letters appearing in a circle around a dot. Your job is to see if there is an X or an N in that circle. If you see an X, press the “X” key and if you see an N, press the “N” key. The letters will appear very quickly, but just do your best. On the left or right side of the circle of letters, you will see a bigger letter. Ignore this letter, and just pay attention to the letters in the circle.”

Participants were then shown two examples of the stimuli and instructed to keep their eyes on the central fixation dot. They completed 3 blocks of 6 practice trials prior to the

experimental trials, with the instructions repeated or re-explained as necessary. Practice trials were excluded from analysis. Once the task began, experimenters refrained from engaging in conversation with the participant. Each experimental block of 96 trials was repeated 5 times (with optional rest periods in between) for a total of 480 trials.

Data Analysis

The dependent variables were total absolute errors and the reaction time from display onset to key press for correct trials. Responses faster than 100 ms or slower than 3000 ms were removed from analysis. Results are first reported directly comparing age effects in a mixed factorial design: 4 (Set Size) x 2 (Distractor Compatibility) x 2 (Group). Results for adults are then reported in a 4 (Set Size) x 2 (Distractor Compatibility) repeated measures ANOVA design, followed by results for children using the same design. Along with significance tests, effect size using eta-squared (η^2), which is interpreted in a manner similar to R^2 (Cohen, 1988), is also reported.

Results

Children vs. Adults

Table 2 provides reaction time and error rate data for children and adults at all eight conditions. Inspection of Table 2 reveals more variability in the child than adult sample, which was confirmed by Levene's test of equality of variance (Winer, 1962). Variances were unequal between groups in all 8 conditions (with $p < 0.01$), violating a key assumption of standard ANOVA. A repeated measures ANOVA using the new "mixed" procedure in SAS was therefore computed. This procedure assumes a compound symmetric structure, and does not assume homogeneity of variance across groups (Littell, Milliken, Stroup, & Wolfinger, 1996).

Unsurprisingly, children were slower than adults, $\underline{F}(1,52) = 33.67, \eta^2 = 0.31, p < 0.001$, and committed more errors, $\underline{F}(1,52) = 77.27, \eta^2 = 0.50, p < 0.001$. Collapsed across set size, children exhibited greater interference from incompatible vs. neutral distractors than adults, for reaction times, $\underline{F}(1,52) = 33.67, \eta^2 = 0.11, p < 0.001$, and error rates, $\underline{F}(1,52) = 77.27, \eta^2 = 0.14, p < 0.001$. Collapsed across distractor type, as set size increased, children demonstrated smaller increases in reaction time than did adults, $\underline{F}(3,156) = 7.56, \eta^2 = 0.10, p < 0.001$, and greater increases in errors, $\underline{F}(3,156) = 7.09, \eta^2 = 0.10, p = 0.002$. The mean reaction time increase between set sizes was 80 ms for adults vs. 49 ms for children. Mean rate of increase for errors between set sizes was 4.68% for adults versus 5.51% for children.

Most important for present purposes was the three way interaction of distractor type and set size with age group. This interaction was significant for reaction times, $\underline{F}(3,156) = 3.22, \eta^2 = 0.06, p = 0.02$, but not for errors, $\underline{F}(3,156) = 1.79, \eta^2 = 0.03, p = 0.15$. Figure 6 illustrates the decrease in interference effect for reaction times. Figure 7 presents interference effects for errors.

Children demonstrated larger reaction time interference effects than adults at set size 1, $\underline{F}(1,52) = 8.26, \eta^2 = .09, p = 0.006$, and set size 2, $\underline{F}(1,52) = 9.19, \eta^2 = .13, p = 0.004$. However, the magnitude of the children's interference was not significantly different than adults at a set size of 4, $\underline{F}(1,52) = 0.15, \eta^2 = .002, p = 0.70$, or a set size of 6, $\underline{F}(1,52) = 0.09, \eta^2 = .001, p = 0.77$ (See Figure 2). The pattern of interference effects with regard to errors was identical to those of reaction times (See Figure 7). Thus at larger set sizes, children's interference control approached that of adults.

In order to examine the potential impact of generally slower speed of processing

on child participants, the interference score at each set size was divided by the reaction time to neutral cues at each set size. This transformation removed the significance of the two-way set size x group interaction, $\underline{F}(3,156) = 1.88$, $\eta^2 = 0.02$, $p = 0.13$. However, even with the ratio transformation, there still remained a general trend of decreasing interference with increasing set size observed.

In order to pursue the specific predictions made about adults versus children, additional analyses were conducted on the data from each age group separately, justified by the significant three-factor interaction of distractor type, set size, and age group.

Adults

The guiding prediction for the young adults was that interference effects would be greater at low than high loads, and that “high” load (inducing early selection and reducing interference) would occur at a set size of 6. As predicted, reaction times were slower for incompatible than for neutral distractors, main effect: $\underline{F}(1,19) = 13.87$, $\eta^2 = 0.42$, $p = 0.001$. Distractor type did not influence error rates, main effect: $\underline{F}(1,19) = 0.14$, $\eta^2 = 0.007$, $p = 0.72$. Due to the larger number of items in the display to be searched, as set size increased, reaction time slowed, $\underline{F}(3,57) = 151.16$, $\eta^2 = 0.89$, $p < 0.001$, and errors increased, $\underline{F}(3,57) = 67.36$, $\eta^2 = 0.78$, $p < 0.001$. There was no significant correlation between number of errors and reaction time at any set size (all $p > .10$) indicating a lack of speed-accuracy trade-off.

In support of the perceptual load hypothesis, as set size increased, interference effects from incompatible distractors decreased as assessed by reaction time (distractor type by set size interaction: $\underline{F}(3,57) = 3.02$, $\eta^2 = 0.14$, $p = 0.04$) and by errors (distractor type by set size interaction: $\underline{F}(3,57) = 4.20$, $\eta^2 = 0.18$, $p < 0.01$). Figures 6 and 7

illustrate an apparent drop in interference from set size 4 to set size 6 confirmed by paired t-tests of reaction time, $t(19) = 7.57$, $p = 0.013$, and error rates, $t(19) = 7.61$, $p = 0.01$. Lavie (1995) directly compared interference scores of reaction times from set sizes 1 and 6. When this analysis was replicated, the greater interference from incompatible distractors at the smaller set size was shy of significance by a two-tailed test, $F(1,19) = 4.13$, $\eta^2 = 0.18$, $p = 0.056$, but significant ($p = .028$) by the one-tailed test justified by the a priori prediction. Results for the college aged participants thus closely replicated prior findings from Lavie's college aged groups (Lavie, 1995; Maylor & Lavie, 1998).

Children

Like the adults, children had slower reaction times, $F(1,33) = 34.41$, $\eta^2 = 0.51$, $p < 0.001$, and higher error rates, $F(1,33) = 18.37$, $\eta^2 = 0.36$, $p < 0.001$ for incompatible than for neutral distractors. Therefore, incompatible distractors created interference for the children, like adults. Also like adults, as set size increased, children's reaction times to target detection increased, $F(3,99) = 21.08$, $\eta^2 = 0.39$, $p < 0.001$, and error rates were greater, $F(3,99) = 63.19$, $\eta^2 = 0.66$, $p < 0.001$, due to the larger number of items in the display to be searched. There was no significant correlation between number of errors and reaction time at any set size (all $p > .05$) indicating a lack of speed-accuracy trade-off effects.

As predicted by the perceptual load hypothesis, as set size increased, interference effects decreased, yielding a distractor type x set size interaction for reaction time, $F(3,99) = 6.73$, $\eta^2 = 0.17$, $p < 0.01$, and error rates, $F(3,99) = 8.13$, $\eta^2 = 0.20$, $p < 0.001$.

Figure 6 illustrates an apparent drop in interference from set size 2 to 4, which was confirmed by a paired t-test, $t(33) = 7.83$, $p = 0.009$. Thus, like adults, children also

showed load-dependent selection processes, but the reduction in interference that signals the onset of early selection was seen at a smaller perceptual load. The developmental difference in the onset of interference reduction was less clear in error rates; like adults, children demonstrated a significant drop in error rate between set sizes 4 and 6, $t(33) = 10.20$, $p = 0.003$ (See Figure 7).

Impact of Very High Error Rates among Children

An examination of overall error rates demonstrated that all the adults, including the seven who had previously been removed from analyses because of pre-existing medical or psychological conditions, performed the attentional task with a mean accuracy rate of 93% and none below an 85% accuracy. When all 27 original adult participants were retained in analyses, despite diagnostic status, they continued to yield a significant distractor type x set size interaction for reaction time, $F(3,78) = 5.80$, $\eta^2 = .18$, $p = 0.01$, and errors, $F(3,78) = 4.94$, $\eta^2 = .16$, $p = 0.003$.

On the other hand, $n = 12$ of the 40 fourth graders were unable to obtain a 67% percent accuracy rate. Removal of these 12 children from analysis (but retaining all other children, regardless of diagnostic status to allow for a larger n) still resulted in a significant distractor type x set size interaction for both reaction times, $F(3,81) = 7.70$, $\eta^2 = .22$, $p < 0.0001$ and errors, $F(3,81) = 10.83$, $\eta^2 = .29$, $p < 0.001$. Note that the effect sizes here are larger than those reported in the initial analyses of the data from the child sample. Thus, removing children who were unable to perform the task with a minimum accuracy increased the strength of the perceptual load effect.

Discussion

Like Lavie (1995) and Maylor & Lavie (1998), interference from peripheral

distractors was reduced by increasing perceptual load in the central search display for college-aged adults. Among these adults, the benefit of larger perceptual load was first apparent at a search set size of 6 in this task paradigm, replicating earlier results rather closely.

The findings further suggested that the attentional mechanisms described in Lavie's (1995) theory of selective attention are operative but not fully mature by the time children are 9-10 years of age. That is, children experienced large interference effects from a competing distractor at low loads, when late selection was presumed to be operative. But, for high loads, when early selection is presumed to be operative, children experienced considerably smaller interference effects with resistance to interference approaching adult levels. This pattern of performance was apparently not due to speed-accuracy trade off effects. Further, children activated early selection, indexed by a reduction in interference relative to the preceding set size, at a smaller set size than adults, a pattern of performance to be expected if they possess a smaller processing capacity. Strikingly, once their capacity was exhausted by task-relevant information at larger set sizes, in terms of absolute reaction time differences between incompatible and neutral distractor conditions, children's ability to ignore irrelevant and competing distractors approached adult levels.

As a group, children were slower overall, which is to be expected from the literature on development of speeded task performance (for a review see Kail, 1991). Controlling for this slowing through proportion transformation removed the group x distractor type x set size interaction, although the trend towards decreasing interference remained. Such an outcome suggests that the speed of processing may interact with or

partially underlie developmental differences in capacity, as has been argued by Kail (1991) and Perfetti (1985) in the literature on development during childhood, and by Salthouse (1996) in the literature on cognitive aging. This issue will be re-addressed in Study 2, however, where the same proportion transformation failed to alter a very similar pattern of results.

In summary, the data of Study 1 revealed a pattern of child versus young adult performance that was almost perfectly analogous to the pattern Maylor and Lavie (1998) reported in comparing older adults to young adults. In their study, older adults were slower as a group than young adults, and at small set sizes, they showed greater interference when distractors were incompatible as opposed to neutral. Like the young adults, their ability to ignore an irrelevant distractor improved at higher set sizes. However, the benefits of increasing perceptual load became apparent at a smaller set size for the older adults, implying that they had smaller perceptual capacities than the young adults.

Study 2

One potential confound in Study 1 concerned changes in the degree of perceptual grouping as set size increases. That is, as more letters are added to the display from set size 1 to set size 6, they increasingly form a “circle” which may serve as an additional cue to participants to aid them in focusing their attention to the relevant items. Thus, reductions in interference from low to high loads may be attributable to a perceptual grouping effect as opposed to increased perceptual loads (Plude & Hoyer, 1985). Although perceptual grouping appears not to have a substantial effect on young adults (Lavie & Cox, 1997), the ability to take advantage of perceptual cues for grouping may

differ in children. Another limitation of Study was its examination of only one child age group. Finally, it was apparent from Study 1 that overall error ratios must be considered carefully in data analysis.

Aims and Hypotheses for Study 2

Study 2 was designed to examine whether (a) the developmental changes in the moderation of selective attention by perceptual load could be accounted for by spatial grouping effects, and (b) to assess effects across additional child age groups. In order to address the first aim, empty locations at set sizes 1, 2, and 4 were marked by placemarkers (i.e. periods “.”), so that each display formed a clear circle of six items (See Figure 8). With that exception, all stimuli and procedures were identical to those of the first experiment. If the larger interference effects demonstrated in Study 1 at set sizes 1 and 2 for the 4th graders was in part due to the 4th graders’ lesser ability to identify and separate the area of the display containing the target in the absence of perceptual grouping cues, then the grouping manipulation would be expected to decrease the interference effect. If the decrease in the interference effect is large enough to equate performance between children and adults, then age differences in performance at the low perceptual loads would be entirely due to the differences in perceptual grouping ability. If age differences remained, they would be attributable to the load-sensitive transition to early selection proposed by Lavie (1995). In order to expand the age range of childhood development examined in the study, another group of young adults, as well as three new groups of children (7-8 year olds, 9-10 year olds, and 11-12 year olds), were recruited in Study 2.

Method

Participants

Young Adults. Twenty-two undergraduates (12 men, 10 women) were recruited from the Department of Psychology's subject pool. Mean age (and sd) was 20.74 (4.68) years with a mean Grade Point Average (and sd) of 2.86 (0.48). All had normal or corrected to normal vision. All performed with a mean accuracy rate of 93%, with none performing below 86% accuracy. All had English as a first language and all were retained for analyses.

Children. Fifty-one 2nd grade children, aged 7-8 (24 boys, 27 girls), twenty-nine 4th grade children, aged 9-10 (17 boys, 12 girls), and twenty 6th grade children, aged 11-12 (7 boys, 13 girls), were recruited from regular education classrooms from five local schools. Because a significant percentage of fourth-grade children were unable to perform the selective attention task with satisfactory accuracy in Study 1, children who performed with an overall accuracy less than 67% were removed from analysis for Study 2. Unsurprisingly, this was a particular issue for the youngest children, many of whom were apparently unable to track the speeded stimuli. This cutoff resulted in a final of $\underline{n} = 26$ (11 boys, 15 girls) second grade children, $\underline{n} = 23$ (12 boys, 11 girls) fourth grade children, and $\underline{n} = 17$ (6 boys, 11 girls) sixth grade children. All methodological and data analytical procedures were otherwise identical to Study 1.

Results

Children vs. Adults

Table 3 provides means and standard deviations for reaction time and error rate for the child and adult groups for all eight conditions. Inspection of Table 3 reveals more variability in the child than adult sample, which was confirmed by Levene's test of

equality of variance (Winer, 1962). Variances were equal across all child groups, but were unequal between all the child vs. the adult age groups. Therefore, as in Study 1, to run a repeated measures ANOVA when comparing adults to children, we used the new "mixed" procedure in SAS assuming a compound symmetric structure without assuming homogeneity of variance across groups.

As in Study 1, the three child groups were slower, $F(3,84) = 88.86$, $\eta^2 = 0.66$, $p < 0.001$, and committed more errors, $F(3,84) = 26.86$, $\eta^2 = 0.46$, $p < 0.001$, than adults. Collapsed across set size, child groups exhibited greater interference from incompatible vs. compatible distractors than adults, yielding a distractor type by age interaction for errors, $F(3,84) = 13.30$, $\eta^2 = 0.20$, $p < 0.001$, but not for reaction time, $F(3,84) = 2.13$, $\eta^2 = 0.04$, $p = 0.10$. Collapsed across distractor type, children also demonstrated greater increases in errors as set size increased than adults, $F(9,252) = 11.98$, $\eta^2 = 0.27$, $p < 0.001$. The mean rate of increase for errors between set sizes was 7.31% for second graders, 6.66% for fourth graders, 5.86% for sixth graders, and 4.04% for adults.

As with Study 1, the three-way interaction with distractor type, set size, and group was significant for reaction times, $F(9,252) = 1.99$, $\eta^2 = 0.07$, $p = 0.04$, but not for errors, $F(9,252) = 0.98$, $\eta^2 = 0.03$, $p = 0.46$. Figure 9 illustrates the reduction in interference with respect to reaction time; Figure 10 with respect to error rates. Age groups differed in the degree of reaction time interference experienced at set size 1, $F(3,84) = 9.70$, $p < 0.001$, but not at set size 2, $F(3,84) = 1.73$, $p = 0.17$, set size 4, $F(3,84) = 0.09$, $p = 0.97$, or set size 6, $F(3,84) = 0.02$, $p = 0.99$.

Post-hoc analyses at set size 1 indicated significant differences in reaction time interference between adults and all child age groups: adults vs. 2nd graders: $F(1,46) =$

14.97, $p = 0.0003$, adults vs. 4th graders: $F(1,43) = 13.11$, $p = 0.0008$, adults vs. 6th graders, $F(1,37) = 5.70$, $p = 0.02$. The child groups did not differ significantly from each other (all $p > 0.28$).

Dividing the interference score at each set size by the reaction time to neutral cues to correct for general overall slowing of the child groups still yielded a significant set size x group interaction, $F(9,252) = 1.97$, $\eta^2 = 0.06$, $p = 0.04$. This outcomes contrasts with that of Study 1 and supports the interpretations of group differences in children.

Adults

All main effects of the task were as expected and replicated those of Study 1. Reaction times were slower for incompatible versus neutral distractors even with the placemaker design, $F(1,21) = 55.08$, $\eta^2 = 0.72$, $p < 0.001$. There was no main effect for distractor type on the number of errors, however, $F(1,21) = 0.85$, $\eta^2 = 0.04$, $p = 0.37$. As set size increased, so did reaction times, $F(3,63) = 102.56$, $\eta^2 = 0.83$, $p < 0.001$, and error rates, $F(3,63) = 80.43$, $\eta^2 = 0.79$, $p < 0.001$. There was no significant correlation between number of errors and reaction time at any set size (all $p > .19$) indicating a lack of speed-accuracy trade-off.

With regards to the perceptual load hypothesis, adults demonstrated a significant distractor type x set size interaction for reaction times, $F(3,63) = 5.66$, $\eta^2 = 0.21$, $p = 0.02$, and errors, $F(3,63) = 14.00$, $\eta^2 = 0.40$, $p < 0.001$ (see Figures 9 and 10). The reduction in interference signaling the onset of early selection was first evident between set sizes 4 and 6, $t(21) = 6.42$, $p = 0.02$, replicating Study 1 even with placemarkers present. But, unlike Study 1, there was also a significant increase in interference with respect to reaction times for adults between set sizes 1 and 2, $t(21) = 10.80$, $p = 0.004$,

indicating that the placemarkers may have enhanced selection processes at the lowest load, when only a single imperative stimulus appeared in the central search set.

Children

As in Study 1, reaction times were slower and error rates higher for incompatible versus neutral distractors for all child age groups. Table 4 provides F , η^2 , and p values for main effects of distractor type and set size, as well as their interactions for all child groups. As set size increased, reaction times and errors to target detection increased for all child age groups. There was no significant correlation between number of errors and reaction time at any set size for any child age group (all $p > .17$), indicating a lack of significant speed-accuracy trade-off effects. Thus, main effects of the task were as expected and replicated Study 1.

As the perceptual load hypothesis would predict, and despite the presence of placemarkers, as set size increased, reaction time interference decreased, yielding significant distractor type x set size interactions for second and fourth grade children. The interaction was not significant for sixth grade children, though the pattern in the means was similar. Evidence from error rates that supported the perceptual load hypothesis, in the form of a distractor type x set size interaction, was significant for all child age groups.

Among second graders, a significant decrease in interference with respect to reaction times was first evident between set sizes 1 and 2, $t(25) = 5.84$, $p = 0.02$. Fourth graders first experienced this decrease between set sizes 2 and 6, $t(1,22) = 14.29$, $p = 0.001$, which is a similar trend in performance as that found in Study 1. Sixth graders demonstrated a reduction in interference which changed more gradually across set size. When sixth-grade performance was tested between set sizes 1 and 6, this change did not

reach significance according to a two-tailed test, $t(1,16) = 3.74$, $p = 0.07$, but was significant ($p = 0.035$) by a one-tailed test justified by the a priori hypotheses. Thus, in comparison to adults who first experienced a decrease in reaction time interference between set sizes 4 and 6, these data suggest that children experience the onset of early selection at smaller set sizes even with the placeholders present. This conclusion is quite clear for second and fourth graders, but the performance of sixth graders was more variable.

Effect of Placeholders: Study 1 vs. Study 2

In order to determine whether placeholders significantly altered results, adults and 4th graders who were able to maintain a 67% accuracy in Study 1 (without placemarkers) and in Study 2 (with placemarkers) were directly impaired. Figure 11 illustrates the reduction in interference with respect to reaction time for fourth graders and adults with and without placeholders; Figure 12 illustrates this with regards to error rate.

The four-way interaction of placemaker status, age group, distractor type, and set size was not significant for reaction times, $F(3,288) = 0.02$, $\eta^2 = 0.00$, $p = 0.99$, though it nearly reached significance for error rate, $F(3,288) = 2.40$, $\eta^2 = 0.02$, $p = 0.07$. Further, none of the three-way or two-way interactions involving placemaker were significant for reaction time (all $p > 0.05$). Although the set x grade x placemaker interaction was significant for errors, $F(3,288) = 2.90$, $\eta^2 = 0.03$, $p = 0.04$, its significance could be attributed to a significant set x grade interaction, $F(3,288) = 22.23$, $\eta^2 = 0.19$, $p < 0.001$, and not to any two-way interactions with placemaker. None of the remaining three-way or two-way interactions involving placemaker were significant for error rate (all $p > 0.20$).

Looking within age groups, for adults, placemarkers did not alter the distractor type x set size interaction with regards to reaction time, $F(3,141) = 0.57$, $\eta^2 = 0.01$, $p = 0.63$, or to error rate, $F(3,141) = 0.91$, $\eta^2 = 0.02$, $p = 0.44$. For children, the distractor type x set size x placemaker interaction was not significant for reaction time, $F(3,147) = 0.10$, $\eta^2 = 0.002$, $p = 0.96$, but was for errors, $F(3,147) = 1.66$, $\eta^2 = 0.18$, $p = 0.03$. Fourth grade children in the no-placemarkers task made an average of 20.12% errors, whereas children in the placemarkers task made an average of 16.62% errors (See Figure 12). However, the overall pattern of decreasing interference with respect to errors as set size increased, remained. Thus, there was no compelling evidence that the placemarkers effect was responsible for the reduction in error interference with increasing set size for either adults or fourth grade children.

Discussion

When placemarkers were added to the selective attention task, at set size 1, fourth and sixth graders demonstrated qualitatively better interference control than second graders, followed by adults who demonstrated the most efficient performance. Despite the qualitative similarities between sixth graders' performance and adults', sixth graders still demonstrated greater interference from distractors at set size 1, indicating that their interference control processes did not yet equal those of adults.

Furthermore, the important set size x distractor type interaction remained significant for all age groups, indicating that early selection was operable by 7-8 years of age, despite overall high error rates as will be discussed below. As perceptual load increased, the degree of interference experienced from competing distractors decreased. This effect remained even after ratio transformation controlled for the overall slower

speed of response in children. These results contrast with findings from Study 1, in which the proportion transformation reduced the three-factor interaction to non-significance. Thus, evidence that developmental changes in processing speed underlie age differences in capacity on this selective attention task is mixed when the results of Study 1 and Study are combined.

As a whole, second graders found it extremely difficult to perform the task in Study 2 with accuracy, which may be in part due to poorer letter recognition skills, especially under the high speed conditions required in this task. Such difficulty resulted in the removal of half of the second grade children in the sample from analysis. But, as one might predict based upon their less mature interference control processes, even those who were able to perform the task with at least a 67% accuracy still experienced the greatest interference at low perceptual loads when late selection was operative.

Study 2 (unlike Study 1) found that for adults, reaction time interference at set size 1 was significantly lower than that at set size 2, suggesting that adults may have greater control than children over the spread of attention when a single abrupt-onset cue calls attention to single stimulus within a task-relevant region of the visual field. However, direct comparison of adults with and without placemarkers yielded no main effect of the presence of placemarkers with regards to reaction time or error rates. Although fourth graders made more errors when placemarkers were absent than when present, the overall pattern of decreasing interference as set size increased with respect to errors, remained.

Taken together, these results suggest that children, like young adults, experience a reduction in interference from low to high set sizes due to the increase in perceptual load,

and that this interference cannot be explained by the impact of perceptual grouping on the allocation of attention. Extending this conclusion, Maylor and Lavie (1998) also failed to find significant effects of placemarkers in their study of older adults. Thus, while perceptual grouping may influence performance on this task to some relatively small extent, the more robust and interesting finding is the demonstration of a developmental trend in selective attention and its sensitivity to perceptual load.

General Discussion of Studies 1 and 2

Parallel results were found in studies 1 and 2 of developmental change in children and in Maylor and Lavie's (1998) study of older adults. This parallel may be easiest to interpret using a general developmental model, which suggests that effortful cognitive abilities that consolidate relatively late in initial development are also the first to weaken in old age. From such a vantage point, it is useful to consider the role of interference control in selective attention.

Recent theorizing has suggested that selective attention is comprised of both the facilitation of a selected signal and the suppression of non-selected signals (Henik & Carr, in press; Klein & Taylor, 1994; Plude et al., 1994). This suppression may be thought of as inhibitory at least in part. In cognition, multiple types of inhibition likely exist and develop at different rates (Henik & Carr, in press; Nigg, 2000). However, the type of inhibition relevant to the current study is best thought of as interference control, which refers to the suppression of distractors to protect performance on a primary task (Dempster, 1993; Nigg, 2000).

Consistent with the general developmental principle that effortful processes take longer to develop than automatic processes, the interference control required in low-load

tasks would be expected to be less efficient in children than in adults (Dempster, 1993; Nigg, Quamma, Greenberg, & Kusche, 1999; Wilson & Kipp, 1998) and would be expected to decline in old age (Zacks & Hasher, 1994; West, 1996). Thus children and older adults should suffer more from having identified an incompatible distractor than would young adults, because they have less ability to control the semantic and motor interference created by such an identified distractor. However, when load is high enough to induce early selection, distractor interference should decrease and its effects should become more comparable across the lifespan, because ignoring distractors is now based on processes that are relatively more automatic (Lavie, 1995) and relatively less age-sensitive. The current study on school-aged children, together with Maylor and Lavie's (1998) study of older adults, suggest that (1) the filtering mechanism which allows for early selection is operating at or near young-adult efficiency in elementary-school-aged children, and likewise is well preserved in older adults, and (2) the benefit of reduced distractor interference conferred by a shift to early, perceptually-based selection under high perceptual loads, is demonstrated at a smaller set size in children and older adults than in young adults.

It is worth emphasizing that the magnitude of the interference suffered at the lowest loads by children in the present study and by older adults in Maylor & Lavie (1998) was substantially larger than the interference suffered at the same loads by young adults. This was particularly true for the youngest children. Yet, once early selection was elicited at a higher load, developmental differences in the magnitude of interference almost disappeared. Thus when the ability to exercise effective interference control is less – among children and older adults – a shift to early selection at a lower perceptual

load is beneficial. That is, the total number of stimuli that are identified, and hence are able to compete for control of action, is smaller, thereby putting less stress on executive control systems that are not as well equipped to adjudicate among them.

Specifically, in Study 2, second graders experienced a significant decrease in interference between set sizes 1 and 2. For the other two groups of children, the decrease in interference was less precipitous, occurring gradually across set sizes—in Study 2, fourth graders experienced a significant decrease in interference between set sizes 2 and 6, and for sixth graders the decrease between set sizes 1 and 6 approached significance ($p = 0.07$). In absolute terms, second graders experienced their greatest decrease in interference between set sizes 1 and 2 (50 ms), fourth graders between set sizes 2 and 4 (40 ms), with adults and sixth graders closely paralleling each other and experiencing the greatest decrease in interference between set sizes 4 and 6 (27 ms for sixth graders, 33 ms for adults).

The implication is that smaller attentional capacity for perceptual processing may compensate for poorer anterior-system efficacy at interference control. With respect to development during childhood, Bjorkland (1997) has argued for the adaptive value of immature cognitive systems that limit the amount of information an infant or child is forced to process. Comparing the data from Studies 1 and 2 to those of Maylor & Lavie (1998) suggests that the same idea applies to the reductions in processing efficiency that occur at the other end of the lifespan.

Summary of Studies 1 and 2

The two studies described here suggest that children's selective attention develops in a way that is consistent with a general model of differential developmental trajectories of effortful (late) versus automatic (early) attentional selection processes. Thus, Lavie's (1995) model is an appealing approach to the study of the development of selective attention, and provides promise for future studies that would assess the functioning of selective attention in children with clinical conditions such as ADHD.

However, as demonstrated in the previous two studies, maintaining minimum accuracy on this task was extremely difficult for children. Error rates were the highest in children aged 7-8, requiring over half the younger sample to be removed from analysis in Study 2. Error rates were also quite elevated in the 9-10 year old group, requiring the removal of 21% of children from analysis. Thus, one concern in Study 3, in which a psychopathological group of children was to be studied, was a careful analysis of error rate data, and an examination of children who were removed from analysis due to high error rates.

Study 3

Having established that perceptual load influences the locus of selection by middle childhood, the aim of the Study 3 was to examine early and late selective attention, as well as response modulation and arousal processes under conditions of high and low visual perceptual loads in children with DSM-IV diagnosed ADD+H and ADD-H.

Depending upon the pattern of data, a significant 3-way group x distractor type x set size interaction could indicate any of the following hypotheses, with the exception of

hypothesis 4 (arousal deficit) which depends upon findings for significant group main effects, but not interactions. Figure 13 illustrates each of the following hypotheses graphically. Specifically:

If **hypothesis 1** (early selective attention deficit) was supported, a significant group x distractor type x set size size interaction would be observed. Normal controls would show worse performance, (i.e. greater reaction time and error rate interference), under conditions of low versus high load perceptual load (See Figure 13a). However, ADD-H or ADD+H children would exhibit equally poor performance regardless of load. If the three-way interaction with diagnostic group is non-significant, however, within-group analyses were planned to determine whether the expected two-way set size x distractor type interaction was observed in the clinically diagnosed children.

If **hypothesis 2** (late selective attention/interference control deficit) was supported, a significant group x distractor type x set size size interaction again would be observed. In this case, however, in comparison to controls, children with ADD-H and/or ADD+H would exhibit greater reaction time and error rate interference at low, but not high, perceptual loads (see Figure 13b).

If **hypothesis 3** (response modulation deficit) was supported, a significant group x distractor type x set size size interaction would again be observed. In comparison to controls, children with ADD-H and/or ADD+H would demonstrate decreased reaction time and error rate interference at low, but not high, loads (see Figure 13c).

If **hypothesis 4** (arousal deficit) was supported, three potential patterns of performance might be predicted. First, there may be a main effect of group on reaction time, number of errors and omissions, and standard deviation of reaction time across

blocks. That is, children with ADD-H and/or ADD+H would demonstrate slower reaction times, increased variability of response, and higher error rates than non-ADHD controls at all time periods. However, there might also be a significant group x set size interaction for standard deviation of reaction times. That is, assuming increasing perceptual load increases the complexity of a task, optimal arousal levels should be higher for low loads and lower for high loads. Therefore, children with ADD+H and/or ADD-H would demonstrate greater variability in response at low loads in which higher levels of arousal are required for optimal task performance, but would equate controls at high loads in which lower levels of arousal are required for optimal task performance. (i.e. see Figure 13d). Lastly, the Yerkes-Dodson model predicts, in a similar fashion to the perceptual load model, that higher levels of arousal restrict attention (resulting in decreased interference from distractors). Thus, if pattern of performance suggestive of an early selective attention deficit (Figure 13a) is found, it might also be interpreted as evidence for an arousal deficit in children with ADHD.

Methods

Participants

In total, 177 children aged 8-12 were recruited and screened for the study from the local community through school mailings and public advertisements. Of those 177, 98 children did not meet screening requirements for one of the three groups (e.g. cutoffs for parent and teacher behavioral rating scales, low IQ, or medical/neurological conditions) and were therefore not eligible to participate. Of the remaining 79 children, based upon both parent and teacher behavioral ratings, there were 34 children with ADD+H (27 boys, 7 girls), 15 children with ADD-H (8 boys, 7 girls), and 30 non-ADHD control children

(14 boys, 16 girls). Ethnicity breakdown was as follows: 71% Caucasian, 14% African American, 9% Hispanic, 2% Other/Mixed, and 4% Unknown/ Undisclosed. As discussed in detail in the Results, children who were unable to maintain a 60% accuracy rate on the experimental task, described below, were removed from analyses of task data. The final n's were ADD+H = 19 (17 boys, 2 girls), ADD-H = 12 (6 boys, 6 girls), and Control = 26 (13 boys, 13 girls). Note that data from 10 of the 26 control children presented here were included in analyses for Study 1.

Overview of Selection Procedure. Children were excluded if they had a primary sensorimotor handicap, frank neurological disorder, pervasive developmental disorder, Tourette's disorder, reading disorder, a Full Scale IQ below 75, or evidence of psychosis. Screening and recruitment were embedded in a larger research project on ADHD directed by Joel Nigg, Ph.D. at Michigan State University.

The screening process for participants had three stages. First, the community-based recruitment utilized school-districts' classification of children. This classification system included information on physical and developmental handicaps and disabilities. Thus, children with documented sensorimotor handicaps were screened out of the potential pool of participants recruited from school mailings and public advertisements. Then, families contacting the study participated in a multi-tiered screening process prior to enrollment. This screening process was as follows:

- 1) Parents first participated in a brief, five minute phone interview during which time they were asked whether their child had (a) normal vision/hearing, (b) a physical handicap, or (c) any major medical, neurological, or psychiatric conditions, and if so, to specify.

- 2) Parents and the child's primary teacher were then mailed a packet of questionnaires to complete regarding the child's behavior. Both packets included the: Behavioral Assessment Rating Scales for Children (BASC; Reynolds & Kamphaus, 1992), Conners' Rating Scales—Revised (Conners'; Conners, 1997), and the ADHD rating scale (DuPaul et al., 1998).

Descriptions of these measures are made in the following section.

- 3) Once these questionnaires were returned by at least one parent and the teacher, and if the child exceeded predetermined empirically-chosen cutoffs for the study, the mother and child were invited to campus to participate in a two hour screening visit to confirm diagnosis. To be included as *potentially* ADHD, child ratings were required to exceed:

- a) The 81st percentile on one of the following parent ratings: BASC attention and/or conduct problem scales (Reynolds & Kamphaus, 1992), the ADHD rating scale of inattention and/or inattention and hyperactivity (DuPaul, 1998), or the Conners' ADHD index (Conners', 1997) *and*:

- b) The 81st percentile on the teacher version of one of these indexes.

However, if children were currently on medication treatment at school, and if the medication was prescribed by a physician who considered teacher ratings, they were considered to exceed school cut-offs for screening purposes. Forty-five of the forty-nine children included as ADD+H or ADD-H for the study exceeded the 90th percentile on the teacher rating scales.

- 4) During the screening visit, the child completed an IQ and reading test (See Cognitive Screening Measures, below). Maternal report of the child's behavior was obtained using a structured diagnostic interview, the Diagnostic Interview Schedule for Childhood for DSM-IV (DISC-IV) (Shaffer, Fisher, Dulcan, & Davies, 1996). Comorbid behavioral disorders were also assessed using the BASC, Conners', and DISC-IV.
- 5) ADD+H and ADD-H diagnoses were confirmed according to DSM-IV (APA, 1994) criteria. Children who met cutoff criteria for ADHD subtypes on the DISC-IV were considered ADHD. They were identified using an "or" algorithm which corresponds to both the procedures used in the DSM-IV field trials for which the ADHD cutpoints are based (Lahey, Applegate, McBurnett, Biederman, et al., 1994), as well as major studies of ADHD including the MTA study (Swanson, Lerner, March, & Gresham, 1999). The "or" algorithm was as follows. If children met age of onset, duration, impairment, and cross-situational criteria, then diagnosis was determined by summing parent-reported symptoms of inattention and hyperactivity on the DISC, with teacher-reported symptoms on the ADHD rating scale which were rated as "quite a bit" or "very much." In 12 cases, symptoms endorsed by the child's teacher were needed to reach diagnostic threshold. For nine of these cases, only one or two teacher symptoms were needed. The remaining three cases required the addition of three or more teacher symptoms, but this appeared to be justified because teacher T-scores on the relevant BASC indexes listed above exceeded the 90th percentile in each case, suggesting significant non-

normative symptomology at school. Cases with 5 symptoms of inattention or hyperactivity were excluded based on field trial data that indicated subtypes could not be reliably determined (Lahey, Applegate, McBurnett, Biederman, et al., 1994). In two cases, age of onset was reported as 8 and 9 respectively; all others were reported at age 7 or younger. These two cases were retained for the study given the lack of empirical support for use of a strict age 7 cutoff (Applegate, Lahey, Hart, Biederman, et al., 1997; Barkley & Biederman, 1997). Results were not dependent on their inclusion, however.

In order to be included in the control group, children were:

- a) below cutoffs (<80th percentile) on all the parent and teacher scales named earlier,
 - b) negative for all subtypes of ADHD on the DISC-IV, with fewer than 4 symptoms in either domain (inattention or hyperactive/impulsive) as calculated by the “or” algorithm, and
 - c) did not have an ADHD sibling according to parent report.
- 6) If, after the screening, the child was eligible to participate, a second on-campus visit was scheduled. At that time the attention task was completed, along with several other measures and tasks that pertained to concurrent studies.

Procedures

Prior to participation, informed written consent from parents was obtained. Verbal assent was obtained from participating children. Parents filled out questionnaires and provided answers in a structured diagnostic interview about their child’s behavior when

they were medication-free. Children engaged in a number of cognitive screening tasks as well as the experimental paradigm. In return for participation, children were given \$5 to participate in the screening process, and \$10 to participate in the full study. Parents were paid \$40 for their participation in the screening process, and \$80 for their participation in the full study.

Medications. Children previously diagnosed with ADHD or ADD were free of short-term psychostimulant medication (e.g. methylphenidate) at least 24 hours prior to the day of testing, and were free of longer-acting stimulants (e.g. Adderall, slow-acting Ritalin, Concerta) at least 48 hours prior to the day of testing. Of the children prescribed medication, 10 were currently prescribed short-acting psychostimulants and 10 were prescribed longer-acting stimulants. Six were on allergy/asthma medication only. The average time children were free of psychostimulants was 80 hrs. for the shorter-acting (range = 29-266 hours) and 80 hrs. for the longer-acting (range = 55-141 hours) stimulants. The short half-life of stimulants (Pelham, 1993) and the minimum 24-48 hour washout period suggests that any medication effects on performance were likely to be minimal. Children taking other longer-acting psychotropic medications (e.g. anti-depressants) were excluded from the study at pre-screening. Asthma inhalers were not used the day of the study; average time children were free of asthma/allergy medication was 37 hours.

Measures

1. Diagnostic Questionnaires

Diagnostic questionnaires and the structured diagnostic interview were chosen for their excellent norms, psychometric properties, broad application, and relevance to

ADHD. The BASC (Reynolds & Kamphaus, 1992), Conners' (Conners, 1997), ADHD Rating Scale (DuPaul et al., 1998), and the DISC-IV (Shaffer et al., 1993) were all used to screen and/or diagnose ADHD in child participants as described earlier. The cut-offs were selected at pre-screen for their ability to identify non-ADHD cases (Conners, Sitarenios, Parker, & Epstein, 1998; DuPaul et al., 1998; Ostrander, Weinfurt, Yarnold, & August, 1998). This was designed to yield few false negatives at pre-screen.

The BASC Teacher Report (TRS) possesses median internal consistency scores for the general sample of children aged 6-14 which range from 0.84-0.90 and test-retest reliability scores ranging from 0.82-0.91. The BASC Parent Report (PRS) possesses test re-test reliabilities range from 0.7-0.88 (Reynolds & Kamphaus, 1992). Both forms of the BASC have demonstrated good specificity and sensitivity for ADHD screening using the cut-offs chosen here (Ostrander et al., 1998).

The Parent Conners'—Revised has 6-8 week test-retest reliability scores of 0.62, 0.85, and 0.72 for the oppositional, hyperactivity, and ADHD subscales, respectively (Conners, 1997). Internal reliability estimates range from 0.86 to 0.94 (Conners, 1997). The Teacher Conners' has 6-8 week test-retest reliability scores of 0.86, 0.72, and 0.80 for the oppositional, hyperactivity, and ADHD subscales, respectively (Conners, 1997). Internal reliability estimates range from 0.77 to 0.96.

The ADHD Rating Scale is a DSM-IV checklist of ADHD symptoms used for diagnostic screening in research and clinical settings (DuPaul et al., 1998). Both parent and teacher versions were normed on a sample of 2000 children ranging in age from 4-20. Test-retest reliabilities for parents and teachers for the total score was 0.85 and 0.90, respectively. Internal reliability estimates were 0.92 and 0.94, respectively. The cutoffs

selected here have good sensitivity and specificity for screening possible ADHD and non-ADHD cases (DuPaul et al., 1998).

The DISC-IV is a structured diagnostic interview developed by NIMH that assesses severity of problem behaviors, remission, and age of onset for nearly all DSM-IV childhood disorders. Validity for the DISC has been previously reported in the literature (Shaffer et al., 1993). In the present study, the following disorders were evaluated: ADHD, ODD, CD, anxiety disorders, depression/dysthymia, tic disorders, OCD, PTSD, and mania according to DSM-IV criteria. A subset of cases only had information from the ADHD, ODD, and CD modules of the DISC-IV due to lack of resources for obtaining the other modules for these cases. The interview is computer aided and administered by program staff after 12 hours of training in its use. Quality and consistency of administration was checked by viewing a random 5% of tapes by the project's principle investigator (Joel Nigg, Ph.D.) and/or an expert from the DISC-IV Development Group at Columbia University (Prudence Fisher, Ph.D.).

2. Cognitive Screening Measures

The research required assessment of general cognitive ability for children. Intelligence was measured using the full battery of the Wechsler Intelligence Scale for Children—III (WISC-III; Wechsler, 1991). The WISC-III standardization sample approximated that of US census data according to age, sex, parent education, race/ethnicity, SES, and geographical region (Wechsler, 1991). For children aged 7-12, Full Scale, Verbal, and Performance IQ on the WISC-III have reliability coefficients between 0.94-0.96, 0.92-0.96, and 0.90-0.91, respectively (Wechsler, 1991). A little over half of the children ($n = 51$) completed a five subtest short form of the WISC (i.e.

Information, Similarities, Vocabulary, Picture Completion, and Block Design) due to constraints in resources; the other children completed the full WISC-III battery. Test-retest reliability of this short form is $r = 0.95$. Validity of the short form in relation to the full battery is $r = 0.90$ (Sattler, 1992).

Reading ability was assessed with the Wechsler Individual Achievement Test Screener Reading test (WIAT Screener; Wechsler, 1992). An IQ-achievement discrepancy as determined through regression methods (Wechsler, 1992), combined with an absolute reading level less than a standard score of 85, was considered indicative of a reading disability (APA, 1994). The WIAT was normed on the same sample as the WISC-III with age-based (6-13 yrs.) reliabilities for reading between 0.91-0.95 (Wechsler, 1992).

3. Selective Attention Paradigm

Because Study 2 found no evidence for significant perceptual grouping effects in school-aged children, the stimuli and procedures for the selective attention paradigm in Study 3 were identical to those used for Study 1. That is, no placemarkers were used to mark empty positions for set sizes 1, 2, or 4 (See Figure 5).

Dependent Variables. As with studies 1 and 2, the dependent variables were total errors and the time to key press for correct trials, with responses faster than 100 ms or slower than 3000 ms removed from analysis. Each block of 96 was repeated 5 times (with optional rest periods in between) for a total of 480 trials. The design for study 3 was: 4 within (Display size) x 2 within (Compatibility) x 3 between (Group). No effects of target or distractor placement were predicted.

Sample Size and Power Analysis

Meta-analysis of ADHD group effects indicate that group effect size in the medium to large range ($f = 0.33$) are typical when an ADHD task deficit is observed (Pennington & Ozonoff, 1996). The data described in Study 1 using the selective attention paradigm for 4th graders (aged 9-10) indicated distractor effects of $f = 1.02$, set size effects of $f = 0.80$, and distractor x set size interaction effects of $f = 0.45$. If these are taken as population effect sizes, given the repeated measures design and these large effect sizes, conservative estimates of power for simple effects as well as all two and three way interactions exceeded 0.90 for the Study 3. The key three way interaction (group x set size x distractor) had a power of 0.80 to detect an effect size of $f = 0.165$, which is a small effect. Effects smaller than that are unlikely to be of clinical significance in view of other known deficits in ADHD.

Despite smaller n 's for the reduced ADD+H ($n = 19$) and ADD-H ($n = 12$) groups, power also exceeded 0.90 for all within-group effects and interactions (i.e. distractor type and set size) due to the robust nature of those effects. However, power for between-groups analyses was weaker. Again assuming ADHD group effects of $f = 0.33$, power to detect simple 3-group between-groups differences was 0.38. Power to detect simple 2-group (ADHD vs. non-ADHD) between groups differences was 0.65. Power was 0.80 to detect a 3-group group effect of $f = 0.55$, and a 2-group effect of $f = 0.40$.

Assuming population correlations of medium effect size ($r = 0.30$) for task performance and behavioral ratings, power for correlational analyses for Study 3 would be 0.63. Power was 0.80 to detect a population $r = 0.37$.

Overall, power for within-subjects analyses were adequate for the primary research questions, but were weaker for secondary between-group and correlational analyses.

Data Reduction and Analysis

The experiment generated a three-factor design with two within-subject factors (display size (4), target compatibility (2)) and one between subject factor (group (3)). Statistical decomposition of the factorial matrix, beginning with higher order interactions, was performed (Keppel, 1982) using a repeated measures ANCOVA procedure, covarying for conduct problems, IQ, reading ability, and age.

Comorbid psychiatric or behavior problems serve as potentially serious confounds to the data gathered in much of ADHD and other clinical research. Therefore, care was taken to control for these effects. The information gathered from the DISC-IV and symptom questionnaires allowed for both dimensional and categorical control of the effects of comorbid disorders and symptoms.

Composite Oppositional Defiant Disorder and Conduct Disorder scores were created for dimensional analysis by taking the means of the T-scores on the Parent and Teacher (1) Conners' Oppositional index, (2) BASC Aggression index, and (3) BASC Conduct Problems Index, as well as (4) the total number of Oppositional Defiant and Conduct Disorder symptoms from the DISC-IV (Alpha Reliability of these seven scales = 0.89). First, symptom scores were covaried among all participants in initial analyses. Then, participants meeting cut-off criteria for such disorders were completely removed from analysis with any remaining subclinical scores covaried.

Results

Justification for removal of children unable to maintain minimum accuracy.

Preliminary consideration was first given to data quality. As demonstrated in Studies 1 and 2, high error rates on this task are common in children, and especially in younger children, due to the high speed conditions under which they are required to scan up to six letters to identify a target. All data analyses in this section refer to the entire sample of children, prior to removal of those unable to maintain a 60% accuracy rate.

Very high error rates suggest that the data are not interpretable because children are unable to correctly engage the task. A 60% minimum accuracy rate cutoff was used for the clinical study. Using a 67% cutoff, as was done for Studies 1 and 2, would have resulted in an insufficient sample size. The decision to lower the accuracy cutoff was justified by the data provided in Figure 14 which illustrates the pattern of performance with regards to reaction time for incorrect responses. For children who were able to maintain a minimum 60% accuracy rate, there was a clear normal distribution of reaction time and a low incidence of omissions. The modal response time for incorrect responses occurred between 700-800 ms. In contrast, the performance distribution for children who were unable to maintain 60% accuracy was right-skewed. These children also had a high incidence of omission errors, and the modal response time fell between 200-300 ms. This discrepant pattern of performance was similar for correct responses as illustrated in Figure 15. Children who performed with greater than 60% accuracy responded more slowly than children who were unable to maintain minimum accuracy, and the pattern of their response time was again normally distributed. The data suggested that children with less than 60% errors were responding rapidly and at random. Because these children were not able to perform the task as intended, their data were not further interpretable.

Unsurprisingly, children who were unable to maintain minimum accuracy were significantly younger (mean age 9.5 years) than children who were able to maintain a 60% minimum accuracy rate (mean age 10.17 years), $F(1,77) = 7.33$, $\eta^2 = 0.09$, $p = 0.008$. Age was not predictive of error rates, $F(1,76) = 2.17$, $\eta^2 = 0.03$, $p = 0.14$, but age did predict hit rate, $F(1,76) = 12.44$, $\eta^2 = 0.14$, $p = 0.001$, and rate of omissions, $F(1,76) = 9.90$, $\eta^2 = 0.11$, $p = 0.002$. That is, older children had a higher hit rate and lower rate of omissions than did younger children.

Broken down by diagnostic groupings, 13% of controls ($n = 4$), 20% of ADD-H children ($n = 3$), and 44% of ADD+H children ($n = 15$) were unable to maintain a 60% accuracy rate on task performance. However, diagnostic groups did not differ in age, $F(2,76) = 1.55$, $\eta^2 = 0.04$, $p = 0.22$, or on the total number of errors and omissions, $F(2,75) = 2.32$, $\eta^2 = 0.06$, $p = 0.11$. Diagnostic groups still did not differ in number of errors and omissions when age was covaried, $F(2,74) = 1.58$, $\eta^2 = 0.04$, $p = 0.21$.

Parent report of hyperactive behavior on the Conners' predicted the total number of errors and omissions, $F(1,71) = 4.34$, $\eta^2 = 0.06$, $p = 0.04$, as did teacher reports of hyperactive behavior on the BASC, $F(1,62) = 5.58$, $\eta^2 = 0.08$, $p = 0.02$, Conners', $F(1,71) = 6.43$, $\eta^2 = 0.08$, $p = 0.01$, and the ADHD rating scale, $F(1,75) = 4.22$, $\eta^2 = 0.05$, $p = 0.04$. That is, the more hyperactive the child, the greater the number of errors and omissions made. However, when age was covaried, only teacher report of hyperactivity on the Conners' remained significant, $F(1,70) = 6.19$, $\eta^2 = 0.08$, $p = 0.01$. All remaining $p > 0.05$. Furthermore, the interaction of age and teacher report of hyperactivity on the Conners' did not predict the number of errors and omissions over and above that of age or hyperactivity alone, $R^2 \text{ change} = 0.21$, $p = 0.43$. Figures 16 and

17 illustrate the pattern of error data broken down by diagnostic groups.

Overall, the evidence supported the removal of children with high error rates. Taken together, regardless of diagnostic group, children who were removed from further task analyses: (1) were on average 6 months younger than children retained for further analysis, and (2) responded to trials impulsively and with random accuracy. Although children with low accuracy rates were rated as more hyperactive on parent and teacher reports, covarying age removed the ability of behavioral ratings to predict error and omission rate for these children with the exception of teacher reports of hyperactivity on the Conners'.

It is likely that the younger children had more difficulty with speeded visual search and letter recognition processes, especially under the high speed conditions required in this task. This appeared especially true of younger children who were rated as more hyperactive by their teachers. Regardless, we can assume that children who had high error rates were either not engaged with the task, or were not processing the stimuli in the same manner as children who were able to maintain minimum accuracy. Including such children in analyses would have lead to invalid findings. Table 5 describes diagnostic groups on rates of errors/hits/omissions, age, IQ, WIAT reading score, and behavioral rating scales, prior to removal of children with high errors. All subsequent data analyses from here only refer to groups after the removal of children unable to maintain a minimum 60% accuracy rate.

Preliminary Description.

Table 6 provides a description of final groups (i.e. excluding those with high errors). Final diagnostic groups (ADD+H, ADD-H, and controls) did not differ in age,

IQ, or WIAT reading scores (all $p > 0.13$). With regards to parent and teacher rating scales, in comparison to controls, ADD+H and ADD-H children had greater levels of inattention and hyperactivity according to the BASC and Conner's indexes listed in Table 6 (all $p < 0.001$), supporting the diagnostic groupings. Eight children with ADD+H, two children with ADD-H, and one non-ADHD control met DSM-IV criteria on the DISC-IV for ODD or CD. One child with ADD+H met criteria as described in Methods for reading disability.

Selective Attention Task

Reaction time and error rate data for all eight conditions are presented in Table 7. Collapsed across distractor type, as set size increased, groups differed in the degree to which they increased reaction time to target detection (set size x group interaction: $F(6,162) = 2.55$, $\eta^2 = 0.09$, $p = 0.02$). The mean reaction time increase between set sizes was 51.16 ms for controls, 37.11 ms for ADD-H children, and 65.98 ms for ADD+H children. Thus, of the three groups, ADD+H children slowed down the most as set size increased. Neither the set size x group interaction with respect to errors, nor the cue type x group interactions for reaction time or error rate, were significant by two-tailed tests (all $p > 0.08$).

With respect to hypothesis 1 (early selective attention), hypothesis 2 (late selective attention), and hypothesis 3 (response modulation deficit), there were no group differences in the degree of interference reduction with increasing set size, suggesting that these processes were intact in children with ADD-H and ADD+H. That is, the three-way group x distractor type x set size interaction was not significant for reaction times, $F(6,162) = 0.41$, $\eta^2 = 0.02$, $p = 0.87$, or for errors, $F(6,159) = 1.44$, $\eta^2 = 0.05$, $p = 0.20$.

Figure 18 illustrates the decrease in interference effects for reaction times. Figure 19 presents interference effects for errors across set sizes. Simple group effects of reaction time and error rate interference at each set size were also compared; all were non-significant (all $p > 0.07$). The significance of the three-way interactions remained unchanged when ADD-H and ADD+H were collapsed and compared against controls.

Results remained unchanged when conduct problems, IQ, age, and reading ability were covaried, and when children with comorbid ODD or CD were removed from analysis with any remaining subclinical conduct scores covaried. Results also remained unchanged when the child with comorbid reading disability was removed from analysis. Sex effects were checked post hoc.¹

In order to pursue specific predictions made about controls versus children with ADD+H and ADD-H with respect to the selective attention deficit, additional analyses were planned on the data within each diagnostic group separately, based on the apriori predictions set forth in the Hypotheses.

Hypothesis 1: Early Selective Attention Deficit

¹ Because participant recruitment was from volunteer community sample, strict control over sex ratios was not possible. No hypotheses with respect to sex effects were predicted, but post hoc analyses were performed, adding sex as a between-groups factor. The four-way set size x distractor type x diagnosis x sex interaction was not significant for reaction time, $F(6,153) = 1.00$, $\eta^2 = 0.04$, $p = 0.42$, or for errors, $F(3,153) = 0.79$, $\eta^2 = 0.03$, $p = 0.58$. With respect to reaction time, none of the two or three-way interactions with sex were significant (all $p > 0.07$) with the exception of the set size x sex interaction, $F(3,153) = 3.86$, $\eta^2 = 0.07$, $p = 0.01$. As set size increased, the average reaction time increase for boys was 63.54 ms vs. 35.32 ms for girls. With respect to errors, none of the two or three-way interactions with sex were significant (all $p > 0.10$) with two exceptions. The three-way distractor type x set size x sex interaction was significant, $F(3,153) = 3.10$, $\eta^2 = 0.06$, $p = 0.03$, with girls experiencing greater error interference at set sizes 1 and 2 than boys. Figure 20 illustrates the decrease in reaction time interference over increasing set size for boys and girls; Figure 21 illustrates this for error interference. The three-way set size x diagnosis x sex interaction was also significant, $F(6,153) = 2.28$, $\eta^2 = 0.08$, $p = 0.04$, with ADD+H girls committing significantly more errors (42%) than ADD+H boys (28%) at set size 6, collapsed across distractor type. Figure 22 illustrates the increase in error rate over increasing set sizes broken down by diagnosis and sex. Because some interactions with sex were found, potential sex effects were also examined in analyses of specific hypotheses.

Controls. Main effects of the task replicated previous findings in children of this age group from Studies 1 and 2, and were as expected. Reaction times were slower, $F(1,25) = 13.23$, $\eta^2 = 0.35$, $p = 0.001$, and error rates were higher, $F(1,53) = 17.19$, $\eta^2 = 0.41$, $p < 0.001$, for incompatible than for neutral distractors. Due to the larger number of items in the display to be searched, as set size increased, reaction time slowed, $F(3,75) = 35.86$, $\eta^2 = 0.59$, $p < 0.001$, and errors increased, $F(3,75) = 100.79$, $\eta^2 = 0.80$, $p < 0.001$. There was no significant correlation between number of errors and reaction time at any set size (all $p > 0.11$) indicating a lack of speed-accuracy trade effects, and supporting interpretations of the reaction time and error rate data.

As predicted by the perceptual load hypothesis, as set size increased, interference effects from incompatible distractors decreased as assessed by reaction time, $F(3,75) = 5.77$, $\eta^2 = 0.19$, $p = 0.001$, and error rate, $F(3,75) = 5.81$, $\eta^2 = 0.19$, $p = 0.001$. The decrease in interference with respect to reaction time was first observed between set sizes 2 and 6, $t(1,15) = 7.56$, $p = 0.01$ (See Figure 18).

Results remained unchanged when conduct problems, reading ability, or age were covaried. Results were also unchanged when children with comorbid ODD or CD were removed from analysis, with any remaining subclinical scores covaried.² When girls were removed from analysis, results for reaction time remained unchanged but due to the reduction in power, the set size x distractor type interaction for errors became non-

² When IQ was entered as a covariate, there was a significant set size x IQ interaction for reaction time $F(3,69) = 4.58$, $\eta^2 = 0.17$, $p = 0.006$, as well as a significant distractor type x IQ interaction for errors, $F(1,23) = 4.37$, $\eta^2 = 0.16$, $p = 0.05$. Reaction time was negatively correlated with IQ at set sizes 1 and 2, and was positively correlated with IQ at set sizes 4 and 6 (all $p > 0.05$). As IQ increased, the number of errors for incompatible distractors significantly decreased, $r = -.49$, $p = 0.01$. These interactions suggest that IQ impacts performance, and implies that the main effects of set size and distractor type cannot be interpreted. However, these interactions were not predicted and cannot clearly be explained. Speculations are deferred.

significant, $F(3,36) = 2.51$, $\eta^2 = 0.17$, $p = 0.07$.

Overall, controls demonstrated the expected main effects of the selective attention task. As predicted by the perceptual load hypothesis, they also demonstrated normal ability to shift the locus of attentional selection from late to early as set size increased.

ADD+H. Main effects of the task replicated those of controls. Reaction times were slower, $F(1,18) = 24.45$, $\eta^2 = 0.58$, $p = 0.001$, and error rates were higher, $F(1,18) = 9.22$, $\eta^2 = 0.34$, $p = 0.008$, for incompatible than for neutral distractors. As set size increased, reaction time slowed, $F(3,54) = 45.00$, $\eta^2 = 0.71$, $p < 0.001$, and errors increased, $F(3,54) = 36.10$, $\eta^2 = 0.67$, $p < 0.001$. There was no significant correlation between number of errors and reaction time at any set size (all $p > 0.25$) indicating a lack of speed-accuracy trade effects.

However, unlike controls, as set size increased, children with ADD+H failed to demonstrate the normal decrease in interference effects with respect to reaction time $F(3,54) = 1.40$, $\eta^2 = 0.07$, $p = 0.25$, suggesting that the early selective attention was not operational. However, children with ADD+H did demonstrate a decrease in interference with respect to errors, $F(3,54) = 4.20$, $\eta^2 = 0.19$, $p = 0.01$. The decrease in interference was observed between set sizes 1 and 6, $t(1,18) = 14.88$, $p = 0.001$ (See Figure 19).

Results remained unchanged when conduct problems, IQ, reading ability, and age were covaried. Results also remained unchanged when children with comorbid ODD or CD were removed from analysis and any remaining subclinical scores were covaried. Results were still unchanged when the child with comorbid reading disability was removed from analysis, or when girls were removed from analysis.

ADD-H. Main effects of the task again replicated those of controls and children

with ADD+H. Reaction times were slower, $F(1,11) = 26.84$, $\eta^2 = 0.71$, $p < 0.001$, and error rates were higher, $F(1,11) = 17.57$, $\eta^2 = 0.62$, $p = 0.002$, for incompatible than for neutral distractors. As set size increased, reaction time slowed, $F(3,33) = 7.20$, $\eta^2 = 0.40$, $p = 0.001$, and errors increased, $F(3,33) = 40.06$, $\eta^2 = 0.78$, $p < 0.001$. There was no significant correlation between number of errors and reaction time at any set size (all $p > 0.40$) indicating a lack of speed-accuracy trade-off effects.

However, like children with ADD+H, as set size increased, children with ADD-H failed to demonstrate the expected decrease in interference effects with respect to reaction time $F(3,33) = 0.80$, $\eta^2 = 0.07$, $p = 0.50$, but did for errors, $F(3,33) = 4.34$, $\eta^2 = 0.28$, $p = 0.01$. The decrease in interference with respect to error rate was observed between set sizes 4 and 6, $t(1,11) = 6.04$, $p = 0.03$ (See Figure 19).

Results remained unchanged when conduct problems, reading ability, and age were covaried.³ Results also remained unchanged when children with comorbid ODD or CD were removed from analysis, and any remaining subclinical scores were covaried. Girls with ADD-H were not removed from analysis due to insufficient sample size.

When children (both boys and girls) with ADD+H and ADD-H were collapsed, the two-way set size x distractor type interaction for the ADHD group more closely approached significance for reaction time, $F(3,90) = 1.98$, $\eta^2 = 0.06$, $p = 0.12$, and was significant for errors, $F(3,90) = 8.51$, $\eta^2 = 0.22$, $p < 0.001$. Overall, there was mixed evidence for an early selective attention deficit in children with either subtype of ADHD.

Hypothesis 2: Late Selective Attention Deficit

³ Like the findings for controls, when IQ was entered as a covariate, there was a significant set size x IQ interaction for reaction time, $F(3,30) = 3.78$, $\eta^2 = 0.27$, $p = 0.02$. Reaction time was negatively correlated

When girls were removed from analysis, error interference at set size 1 was positively and significantly correlated with parent ratings on the Conners' hyperactivity ($r = .43, p = 0.01$) and global ADHD indices ($r = .40, p = 0.02$), as well as the total score on the ADHD rating scale ($r = .38, p = 0.02$). Although shy of significance, error interference at set size 1 was positively correlated with parent ratings of hyperactivity ($r = .28, p = 0.10$) and inattention ($r = .32, p = 0.054$) on the BASC, as well as the hyperactivity index of the ADHD rating scale ($r = .31, p = 0.06$). Teacher ratings of hyperactivity on the BASC were shy of significance at the same set size ($r = .32, p = 0.06$). None of the above correlations remained significant when girls were included (all $p > 0.06$).

When ADD+H and control boys were compared on task performance (ADD-H boys were not included due to small sample size), the three-way distractor type x set size x diagnosis interaction was non-significant for reaction time, $F(3,84) = 0.50, \eta^2 = 0.02, p = 0.69$, but was significant for errors, $F(3,84) = 3.34, \eta^2 = 0.11, p = 0.02$. That is, at set size 1, control boys demonstrated less interference with respect to errors than ADD+H boys, $F(1,28) = 7.76, \eta^2 = 0.22, p = 0.009$. This was not true at other set sizes. Figure 23 illustrates the decrease in interference over increasing set sizes for reaction time; Figure 24 does this for errors. There were no significant speed-accuracy trade off effects in either the control or ADHD boys (all $p > 0.37$). Results remained unchanged when age was covaried.

None of the two-way interactions with diagnosis for reaction time or errors were significant (all $p > 0.08$). Results remained unchanged when ADD-H and ADD+H boys

with IQ at each set size (all $p > 0.22$). Again, any speculations regarding this interaction are deferred.

were collapsed and compared with controls. Girls alone were not examined due to small sample size.

Overall, despite the lack of group differences in the three-way group x distractor type x set size interaction prior to the removal of girls and children with ADD-H from analysis, there was evidence for a cognitive interference control deficit at least for combined subtype boys, partially supporting a late selective attention deficit.

Hypothesis 3: Response Modulation Deficit

As predicted by the response modulation hypothesis, error interference at set size 2 was negatively and significantly correlated with parent ratings of hyperactivity on the BASC ($r = -.28$, $p = 0.03$), Conners' ($r = -.33$, $p = 0.02$), ADHD rating scale ($r = -.31$, $p = 0.02$), as well as teacher ratings of total symptomology on the ADHD rating scale, ($r = -.27$, $p = 0.05$). Error interference at set size 4 was also significantly and negatively correlated with parent ratings of hyperactivity on the BASC ($r = -.30$, $p = 0.02$) and the ADHD rating scale ($r = -.28$, $p = 0.03$). That is, children who were rated as more hyperactive according to parent and teacher report experienced less interference with respect to errors. When girls were removed from analysis, none of the above correlations remained significant.

The correlational evidence reported here provide weak support for the presence of a response modulation deficit in children with ADD+H if the perceptual load paradigm can be used to test the response modulation hypothesis. Furthermore, these negative correlations of behavioral ratings with error rate data contradict the positive correlations with reaction time data presented in the previous section on late selective attention.

Hypothesis 5: Arousal Deficit

Despite frequent findings of slower and more variable reaction times on reaction time tasks for ADD-H and ADD+H children, groups did not differ either in their mean reaction time, $F(2,54) = 0.21$, $\eta^2 = 0.008$, $p = 0.81$, or the standard deviation of their reaction times, $F(2,54) = 0.38$, $\eta^2 = 0.01$, $p = 0.69$. Groups also did not differ in the number of errors or omissions committed, $F(2,54) = 1.16$, $\eta^2 = 0.04$, $p = 0.32$.

Although reaction times during the first block of trials was significantly longer than reaction times to the last block of trials, $F(4,216) = 2.41$, $\eta^2 = 0.04$, $p = 0.05$, and although the number of error and omissions was also greater during the first vs. last block, $F(4,216) = 2.55$, $\eta^2 = 0.05$, $p = 0.04$, there were no block x group interactions (all $p > 0.32$). There was no main effect of block for standard deviation, $F(4,216) = 1.46$, $\eta^2 = 0.03$, $p = 0.21$. Main effects of block for reaction time and number of omissions and errors became non-significant when girls and children with ADD-H were removed from analysis. Figure 25 illustrates the change in reaction time, Figure 26 illustrates the change in standard deviation of reaction time, and Figure 27 illustrates the change in the number of errors and omissions committed across successive blocks.

The three-way group x set size x distractor type interaction for standard deviation of reaction time was not significant, $F(6,162) = 1.17$, $\eta^2 = 0.04$, $p = 0.33$, suggesting that children with ADHD were not more variable than controls at lower set sizes. Figure 28 illustrates the change in mean standard deviation of reaction time across set sizes. According to the Yerkes-Dodson model of arousal, the pattern of performance predicted for that of an early selective attention deficit could also be a predicted pattern of behavior for a deficit in arousal. However, as stated previously, there were no group differences for the shift from late to early selection with increasing set size. Overall, there appears to

be no evidence from this task for an arousal deficit in children with ADD+H or ADD-H.

Discussion

Overall, in Study 3, evidence for early selective attention, late selective attention, response modulation, and arousal deficits in ADHD was mixed at best, and non-existent at worst. With respect to early selective attention, within-group analyses demonstrated a lack of normal reduction in reaction time interference with increasing set size for children with ADD+H and ADD-H. The lack of a set size x distractor type interaction would seem to indicate failure to shift from late to early selection under high perceptual loads.

However, normal reduction in error rate interference with increasing set size was evident for both ADHD subtypes. Furthermore, the three-way group x distractor type x set size interaction, which would have been the strongest indicator of group differences in early selective attention processes, was not significant for either reaction times or for error rates, implying a lack of group differences. Due to the unequal distribution of sex within diagnostic groups, sex effects were checked for each of the hypotheses. Results for early selective attention hypothesis remained unchanged when girls were removed from analysis, so it is unlikely that sex effects were responsible for the lack of findings.

With respect to the late selective attention hypothesis, although shy of significance, parent and teacher ratings of hyperactivity and inattention were positively correlated with reaction time interference at set size 2. When girls were excluded from analysis, boys with ADD+H had greater error (but not reaction time) interference at set size 1 than control boys. Because low loads (i.e. set size 1 and 2) require interference control to protect performance, this pattern of results suggests that the ADD+H boys had a deficit in interference control. Unlike the strong evidence for ADD+H deficits in

suppressing a primary, intended motor response on cue (e.g., go-no-go or stopping tasks), evidence to support interference control deficits in children with ADHD, primarily based upon findings from the Stroop task, has been weak to inconclusive (Nigg, 2001). Part of the difficulty in the isolation of this deficit may be because these processes are developmentally immature even for non-ADHD children, making group differences more difficult to detect at these ages. Indeed, the strongest evidence for an interference control deficit in ADHD comes from studies of adolescents (Nigg, 2001).

As discussed within the literature review, previous studies of selective attention in ADHD did not control for perceptual load, and frequently failed to include competing distractors which would have provided motivation for attentional focus and selection. In Study 3, the diagnostic groups were carefully screened and selected for inclusion in the study following empirically supported guidelines, and the data were likewise meticulously examined to remove children from analysis if there were suspicions regarding the validity of task performance. In carefully attending to these methodological concerns, Study 3 found some evidence (although inconclusive) that children with both ADD+H and ADD-H demonstrate deficits in early and late selective attentional processes.

With respect to the response modulation hypothesis, higher levels of ADHD symptomology were associated with lower levels of error rate interference at set sizes 2 and 4. When girls were removed from analysis, these correlations became non-significant. Recall that decreased interference at low (but not high) loads was hypothesized to reflect a response modulation deficit. It is not clear whether the perceptual selection described for this task is comparable to the automatic monitoring

processes as described by Newman and Wallace (1993b). Unlike the selective attention paradigm tested here, the tasks described by Newman and colleagues do not explicitly instruct participants to ignore peripheral information, and participants are not informed as to the relevance or irrelevance of the peripheral information as in the current studies. Rather, good performance on their tasks, which were designed specifically to measure response modulation processes, require that participants utilize peripheral feedback in the evaluation of their performance (Newman & Wallace, 1993b). According to the theory, psychopaths and other individuals with behavioral regulation disorders are less able to automatically monitor this peripheral information.

But, if the processes in this paradigm and Newman's are the same, then the pattern of correlations observed here would be somewhat consistent with the response modulation hypothesis. Keep in mind, however, that children between the ages of 9-10 first evidenced a reduction in interference at a set size of 4 (as described in Study 1). Thus, in children of this age group, set sizes 1 and 2 can be considered "low loads," and set sizes 4 and 6 can be considered "high loads." The predicted pattern of data based on the response modulation theory was that ADHD children would show better interference control at low loads, but that groups would equalize at high loads as early selective attentional processes were initiated in non-ADHD children. To give the response modulation theory the benefit of the doubt, it is possible that individuals with response modulation deficits could demonstrate better interference control than non-ADHD controls for low as well as high loads.

However, if these error rate results are accepted, then one must also recognize that they are in direct contradiction to the reaction time findings reported as evidence for an

interference control deficit. Whereas ADHD symptom ratings were positively correlated with reaction time interference at set sizes 1 and 2 (late selective attention deficit), they were negatively correlated with error rate interference at set sizes 2 and 4 (response modulation deficit). ADHD children cannot be both better and worse at controlling interference effects from incompatible distractors. Because there was no evidence for speed-accuracy trade-off effects, the contradiction is puzzling and cannot easily be explained. However, because group differences for error interference between non-ADHD and ADD+H boys supported the interference control hypothesis, but not the response modulation hypotheses, the weight of evidence is slightly greater for the former than for the latter.

There was no evidence for an arousal deficit in ADHD children in Study 3. Slower and more variable reaction time at the outset of a task, which does not deteriorate more than controls over time has historically been attributed to deficits within the arousal system, although Sergeant et al. (1999) has suggested that such performance is more indicative of deficits in activation or effort. Despite frequent findings in the literature for slower and more variable performance on speeded response tasks in children with ADD+H and ADD-H (Douglas, 1999), no significant group differences were found in the current study. Variability in performance also did not differ according to task complexity, and no evidence was found that children with ADHD were unable to narrow their attention at high set sizes due to hypoarousal. However, alternative explanations aside from negative findings for an arousal deficit, are possible. For instance, it may be that the ADHD group recruited for this study differ in some fundamental manner from those recruited in other speeded-response studies, or it may simply be a reflection of the

measure used in the current studies. Given the strict screening and recruiting guidelines which follow those of the DSM-IV field trials as well as other major studies, it is highly unlikely that the selection of the ADHD group was flawed or invalid. But, with respect to task differences, the stopping task, where such slower and more variable responding has been noted (Nigg, 2001), explicitly emphasizes speeded performance. In the present selective attention paradigm, although children were instructed to respond to the target as soon as it was identified, accuracy rather than speed was emphasized by feedback tones to incorrect trials.

Difficulties and Limitations in Interpretation

Ideally, analyses of task data would be consistent for both reaction time and error rate data, and such consistency would be the best test of the proposed hypotheses. This was not the case with the two most intriguing findings. With respect to the early selective attention hypothesis, children with ADD+H and ADD-H did not experience normal reduced interference from incompatible distractors with increasing set size for reaction time, but did show the normal response pattern for errors. With respect to the cognitive interference control hypothesis, boys with ADD+H experienced greater error interference at set size 1 than non-ADHD boys, but this deficit was not apparent with reaction time data. In both cases, key 3-way interactions did not reach significance.

When faced with these partial findings, interpretation of the reaction time data is likely more valid than interpretation of error rate data, although this does not suggest that error rate data is invalid. After selecting out children with extremely high error rates, alpha reliability of the reaction time measures was 0.98, only slightly exceeding the reliability of 0.90 for errors. Of the two, reaction time data is also more easily interpreted,

and tends to provide more detailed examination of group differences in performance. That is, in Studies 1 and 2, developmental differences in performance were noticeable upon examination of reaction time, but not error rate data. Further, children with extremely high error rates had been removed from analysis, and although examination of the pattern of errors suggested that these children were not attending to the task, their removal was based upon their error rates, which may have had an unexpected or unpredicted influence on the interpretation of the error rate data.

Prior to making more conclusive statements for early and late selective attention deficits in children with ADHD, a much stronger replication of Study 3 results would first be warranted.⁴ Like ADD-H and ADD+H children in Study 3, sixth graders in Study 2 also failed to demonstrate a significant reduction in reaction time interference with increasing set size, but did demonstrate the expected drop with respect to errors. It is unlikely that early selective attention processes are deficient or that the perceptual load model does not apply to sixth graders, when it does for individuals both younger and older than them. Rather, it may be that the sample effect sizes observed in Study 1 do not represent the population effect sizes, so that power was much lower than estimated. Both the 6th graders ($n = 17$) as well as the ADD+H ($n = 19$) and ADD-H ($n = 12$) groups had smaller n 's than other groups of children, and may simply have required larger sample sizes before the perceptual load effect could be detected.

Theoretical and Clinical Implications. To give the early and late selective attention findings the benefit of the doubt, if these findings did replicate more strongly,

⁴ Replication is particularly important given variable findings from other tests of posterior-parietal attentional processes (e.g., covert orienting). However, the selective attention processes described here are not identical to those tested in the covert orienting tasks, and may not map to the same neuroanatomical regions or generalize.

there are a number of theoretical and clinical implications which could be made. Recall that early selection of perceptual features is likely dependent upon the functioning of the parietal and temporoparietal cortex (Arrington, Meyer, Carr, & Rao, 2000; Gitelman, Nobre, Parrish, LaBar, Kim, Meyer, & Mesulam, 1999). On the other hand, late selection of semantic meanings is likely dependent upon more anterior networks including the anterior cingulate gyrus and regions of the prefrontal cortex (Cabeza & Nyberg, 1997). Data from Studies 1 and 2 argue that children's smaller attentional capacities initiate the onset of early selective attention in order to protect against immature interference control processes.

Thus, children with ADHD may have neurological deficits in posterior attentional systems. If this early selective attention process is not as efficient for children with ADHD, there also would be greater downstream strain upon the anterior executive interference control processes, as they attempt to compensate or deal with the additional irrelevant information. This processing strain theoretically could lead to behavioral symptoms of inattention. For combined subtype boys, the challenge may be even greater due to additional deficits in late selective attention. If this were the case, current theories which predominantly stress inhibitory dysfunctions of motor response (Barkley, 1997b), or of poor activation in the motor output stage of processing (Sergeant et al., 1999) would have to be modified to accommodate not only the positive findings for early selective attention deficits, but also for cognitive (not merely motor) interference control deficits. Clinically speaking, performance patterns on the perceptual load paradigm could be used as an objective measure to aid the identification and diagnosis of childhood ADHD, and potentially to predict treatment response for subgroups of ADHD.

If, however, these results did not replicate and further study indicated that neither subtype of ADHD demonstrated deficits in early or late selective attention, then Douglas (1999) would have to make alterations to her theory of dysfunctional effort allocation to explain why children with ADHD are able to allocate sufficient effort to a selective attention task, but not to motor inhibitory tasks such as go-no-go or stopping. Furthermore, if the somewhat slower and more variable reaction time performance in children with ADHD on this task continued to be non-statistically different than those of non-ADHD controls, suggesting that the effort system (as Sergeant et al. (1999) have argued) functions within normal limits, then those theories (e.g. Douglas, 1999; Sergeant, 1999) relying in part on this pattern of performance would be forced to explain the difference. The clinical relevance to these negative findings would be added evidence that selective attention, defined by the perceptual load model, is not impaired in children with ADHD. Theoretically, that conclusion would add weight to theories stressing prefrontal and/or basal ganglia executive control processes as involved in ADHD.

Conclusion

Lavie's (1995) perceptual load model is an appealing approach to the study of the development of selective attention in both normal and abnormal development. The advantages of this model for such studies are that it allows for an integration of the early and late selection approaches, and is able to account for the apparently contradictory results generated by these two opposing camps, while capturing trends in attentional selectivity across the lifespan.

However, in young children and children with ADHD, high error rates resulted in the removal of a large percentage of children from analysis, suggesting that the task as

designed for adults may not be ideal for children. In order to address this problem, future studies could consider increasing the stimulus display time. Color or simple picture targets, as opposed to letters, may also help reduce error rates for children whose letter recognition skills may not as efficient as older children or adults. Trials in which errors occurred could also be repeated until a minimum accuracy rate was reached, but practical considerations including the experimental run time, as well as child frustration, should be considered.

Aside from future studies providing stronger replication of results, studying the problem of selective attentional functioning in childhood ADHD from alternative vantage points would also be a future direction. For example, appropriately-designed dual-task paradigms, stressing the importance of both primary and secondary task performance, could be used to measure attentional capacity. Examination of late selective attentional functioning in trial-by-trial flanker-type tasks in children and adolescents with ADHD is another potential study. Not only would such a study allow for a clarification of the role of interference control in ADHD, but would also provide a map of its development in pathological development.

Regardless, the present results suggest that Lavie's (1995) selective attention paradigm is an informative measure of attentional filtering across a large portion of the lifespan, and that taking into account the impact of perceptual load on early versus late selection boosts the conceptual and empirical power of theories regarding the development of both normal and abnormal attention.

REFERENCES

- Alberts, E. & van der Meere, J. (1992). Observations of hyperactive behaviour during vigilance. Journal of Child Psychology and Psychiatry, 8, 1355-1364.
- American Psychiatric Association. (1994). Diagnostic and statistical manual of mental disorders (4th ed.). Washington, D.C.: Author.
- American Psychiatric Association. (1987). Diagnostic and statistical manual of mental disorders (3rd ed., revised). Washington, D.C.: Author.
- American Psychiatric Association. (1980). Diagnostic and statistical manual of mental disorders (3rd ed.). Washington, D.C.: Author.
- Applegate, B., Lahey, B., Hart, E., Biederman, J., Hynd, G., Barkley, R. et al. (1997). Validity of the age-of-onset criterion for ADHD: A report from the DSM-IV field trials. Journal of the American Academy of Child and Adolescent Psychiatry, 36, 1211-1211.
- Arrington, C. M., Meyer, A. R., Carr, T. H., & Rao, S. M. (2000). Neural mechanisms of visual attention: Deploying and reorienting attention in space. Journal of Cognitive Neuroscience, 12 (Supplement 2), 106-117.
- Barch, D. M., Braver, T. S., Sabb, F. W., & Noll, D. C. (2000). Anterior cingulate and the monitoring of response conflict: Evidence from an fMRI study of overt verb generation. Journal of Cognitive Neuroscience, 12, 298-311.
- Barkley, R. (1997b). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. Psychological Bulletin, 121, 65-94.
- Barkley, R. (1996). Attention deficit/hyperactivity disorder. In Mash, E.J. & Barkley, R.A. (Eds.), Child Psychopathology (pp. 63-112). New York: Guilford Press.
- Barkley, R., Anastopoulos, A., Guveremont, D., & Fletcher, K. (1991). Adolescents with ADHD: Patterns of behavioral adjustment, academic functioning, and treatment utilization. Journal of the American Academy of Child and Adolescent Psychiatry, 30, 752-76.
- Barkley, R. & Biederman, J. (1997). Toward a broader definition of the age-of-onset criterion for attention-deficit hyperactivity disorder. Journal of the American Academy of Child and Adolescent Psychiatry, 36, 1204-1210.
- Barkley, R., DuPaul, G., & McMurray, M. (1990). Comprehensive evaluation of attention deficit disorder with and without hyperactivity as defined by research criteria. Journal of Counseling and Clinical Psychology, 58, 775-789.

Barkley, R. (1992). Frontal lobe functions in attention deficit disorder with and without hyperactivity: A review and research report. Journal of Abnormal Child Psychology, 20, 163-188.

Biederman, J., Newcorn, J., & Sprich, S. (1991). Comorbidity of attention deficit hyperactivity disorder with conduct, depressive, anxiety, and other disorders. American Journal of Psychiatry, 148, 564-577.

Bjorkland, D. (1997). The role of immaturity in human development. Psychological Bulletin, 122, 153-169.

Broadbent, D. (1958). Perception and communication. London: Pergamon Press.

Browning, R. (1967). Effect of irrelevant peripheral visual stimuli on discrimination learning in minimally brain-damaged children. Journal of Counseling Psychology, 31, 371-376.

Bush, G., Frazier, J., Rauch, S., Seidman, L., Whalen, P., Jenike, M., Rosen, B., & Biederman, J. (1999). Anterior cingulate cortex dysfunction in attention-deficit/hyperactivity disorder revealed by fMRI and the counting stroop. Biological Psychiatry, 45, 1542-1552.

Cabeza, R. & Nyberg, L. (1997). Imaging cognition: An empirical review of PET studies with normal subjects. Journal of Cognitive Neuroscience, 9, 1-26.

Carlson, C. & Mann, M. (in review). Sluggish cognitive tempo predicts more severe impairment in ADHD, predominantly inattentive type.

Carter, C., Krener, P., Chaderjian, M., Northcutt, C., & Wolfe, V. (1995). Abnormal processing of irrelevant information in attention deficit hyperactivity disorder. Psychiatry Research, 56, 59-70.

Casey, B., Castellanos, F., Giedd, J., Marsh, W., Hamburger, S., Schubert, A., Vauss, Y., Vaituszia, C., Dickstein, D., Sarfatti, S., & Rapoport, J. (1997). Implication of right frontostriatal circuitry in response inhibition and attention-deficit/hyperactivity disorder. Journal of the American Academy of Child and Adolescent Psychiatry, 36, 374-383.

Ceci, S. & Tishman, J. (1984). Hyperactivity and incidental memory: Evidence for attentional diffusion. Child Development, 55, 2192-2203.

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences—2nd Ed. Hillsdale, NJ: Erlbaum Associates.

Cohen, N. & Douglas, V. (1972). Characteristics of the orienting response in hyperactive and normal children. Psychophysiology, 9, 238-245.

Conners, K., Sitarenios, G., Parker, J., & Epstein, J. (1998). The revised Conners' parent rating scale (CPRS-R): Factor structure, reliability, and criterion validity. Journal of Abnormal Child Psychology, 26, 257-268.

Conners, K. (1997). Conners' Rating Scales-Revised Technical Manual. NY: Multi Health Systems.

Corbetta, M. (1998). Frontoparietal cortical networks for directing attention and the eye to visual locations: Identical, independent, or overlapping neural systems? Proceedings of the National Academy of Sciences of the USA, 95, 831-838.

Dalebout, S., Nelson, N., Hletko, P., & Frentheway, B. (1991). Selective auditory attention and children with attention-deficit hyperactivity disorder: Effects of repeated measurement with and without methylphenidate. Language, Speech, and Hearing Services in Schools, 22, 219-227.

Davidson, E., & Prior, M. (1978). Laterality and selective attention in hyperactive children. Journal of Abnormal Child Psychology, 6, 475-481.

Dempster, F. (1993). Resistance to interference: Developmental changes in basic processing mechanisms. In M.L. Howe and R. Pasnak (Eds.), Emerging Themes in Cognitive Development (Vol 1, pp. 3-27). New York: Springer-Verlag.

de Sonnevile, L., Njokiktjen, C., & Hilhorst, R. (1991). Methylphenidate-induced changes in ADHD information processors. Journal of Child Psychology and Psychiatry, 32, 285-295.

Deutch, J. & Deutch, D. (1963). Attention: Some theoretical considerations. Psychological Review, 70, 80-90.

Douglas, V. (1999). Cognitive control processes in attention-deficit/hyperactivity disorder. In Quay, H. & Hogan, A., Handbook of Disruptive Behavior Disorders, (pp.105-138). New York: Kluwer Academic.

Douglas, V. (1983). Attentional and cognitive problems. In M. Rutter (Ed.) Developmental Neuropsychiatry, (pp.280-329). New York: Gilford.

DuPaul, G., Power, T., Anastopoulos, A., & Reid, R. (1998). ADHD Rating Scale-IV: Checklists, Norms, and Clinical Interpretation. NY: Guildford Press.

Enns, J. (1993). What can be learned about attention from studying its development? Canadian Journal of Psychology, 34, 274-281.

Enns, J., & Akhtar, N. (1989). A developmental study of filtering in visual attention. Child Development, 60, 1188-1199.

Enns, J., & Girgus, J. (1985). Developmental changes in selective and integrative visual attention. Journal of Experimental Child Psychology, 40, 319-337.

Epstein, H.T. (1986). Stages in human brain development. Brain Research, 395, 114-119.

Eysenck, M. (1982). Attention and Arousal. New York, NY: Springer-Verlag.

Faraone, S., Biederman, J., Weber, W., & Russel, R. (1998). Psychiatric, neuropsychological, and psychosocial features of DSM-IV subtypes of attention-deficit hyperactivity disorder: Results from a clinically referred sample. Journal of the American Academy of Child and Adolescent Psychiatry, 37, 185-193.

Friedrich, F. J., Egly, R., Rafal, R. D., & Beck, D. (1998). Spatial attention deficits in humans: A comparison of superior parietal and temporal-parietal junction lesions. Neuropsychology, 12, 193-207.

Gaub, M. & Carlson, C.L. (1997). Gender differences in ADHD: A meta-analysis and critical review. Journal of the American Academy of Child and Adolescent Psychiatry, 36, 1036-1045.

Geen, R. (1984). Preferred stimulation levels in introverts and extraverts: Effects on arousal and performance. Journal of Personality and Social Psychology, 46, 1303-1312.

Giedd, J., Castellanos, X., Casey, B., Kozuch, P., King, A.C., Hamburger, S., Rapoport, J. (1994). Quantitative morphology of the corpus callosum in attention deficit hyperactivity disorder. American Journal of Psychiatry, 151, 665-669.

Gitelman, D. R., Nobre, A. C., Parrish, T. B., LaBar, K. S., Kim, Y. H., Meyer, J. R., & Mesulam, M. M. (1999). A large-scale distributed network for covert spatial attention: Further anatomical delineation based on stringent behavioral and cognitive controls. Brain, 122, 1093-1106.

Goodyear, P. & Hynd, G. (1992). Attention deficit disorder with (ADD/H0 and without (ADD/VO) hyperactivity: Behavioral and neuropsychological differentiation. Journal of Clinical Child Psychology, 21, 273-305.

Gray, J. (1987). The psychology of fear and stress. New York: Cambridge University Press.

Halperin, J. (1991). The clinical assessment of attention. International Journal of Neuroscience, 58, 171-182.

Harnishferger, K. (1995). The development of cognitive inhibition: Theories,

definitions, and research evidence. In F.N. Dempster & C.J. Brainerd (Eds.), Interference and Inhibition in Cognition (pp. 175-204). New York: Academic Press.

Heilman, K. & Van Den Abell, T. (1979). Right hemisphere dominance for mediating cerebral activation. Neuropsychology, 17, 315-321.

Heilman, K., Voeller, K., & Nadeau, S. (1991). A possible pathophysiologic substrate of attention deficit hyperactivity disorder. Journal of Child Neurology, 6, S74-S79.

Henik, A., & Carr, T. H. (in press). Inhibition. In V. S. Ramachandran (Ed.), Encyclopedia of the human brain. San Diego: Academic Press.

Hooks, K., Milich, R., & Lorch, E. (1994). Sustained and selective attention in boys with attention deficit hyperactivity disorder. Journal of Clinical Child Psychology, 23, 69-77.

Houghton, S., Douglas, D., West, J., Whiting, K., Wall, M., Langsford, S., Powell, L., Carroll, A. (1999). Differential patterns of executive function in children with attention-deficit hyperactivity disorder according to gender and subtype. Journal of Child Neurology, 14, 801-805.

Huttenlocher, P.R., & Dabholkar, A.S. (1997). Developmental anatomy of prefrontal cortex. In N.A. Krasnegor, G.R. Lyon, & P.S. Goldman-Rakic (Eds.), Development of the prefrontal cortex: Evolution, neurobiology, and behavior (pp. 69-83). Baltimore: Paul H. Brookes Publishing Co.

Hynd, G., Semrud-Clikeman, M., Lorys, A., Novey, E., Eliopoulos, D., & Lyytinen, H. (1991). Corpus callosum morphology in attention deficit-hyperactivity disorder: Morphometric analysis of MRI. Journal of Learning Disabilities, 24, 141-146.

Jonkman, L., Kemner, C., Verbaten, M., van Engeland, H., Kenemans, J., Camfferman, G., Buitelaar, J., & Koelega, H. (1999). Perceptual and response interference in children with attention-deficit hyperactivity disorder, and the effects of methylphenidate. Psychophysiology, 36, 419-429.

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. Psychological Bulletin, 109, 490-501.

Keppel, G (1982). Design and analysis: A researcher's handbook (2nd Ed.) Englewood Cliffs, NJ: Prentice Hall.

Klein, R., & Taylor, T. (1994). In D. Dagenbach & T. H. Carr (Eds), Inhibitory processes in attention, memory, and language. San Diego: Academic Press.

Lahey, B., Applegate, B., McBurnett, K., Biederman, J., Greenhill, L., Hynd, G.,

Barkley, R., Newcorn, J., Jensen, P., Richters, J., Garfinkel, B., Kerdyk, L., Frick, P., Ollendick, T., Perez, D., Hart, E., Waldman, I., & Shaffer, D. (1994). DSM-IV field trials for attention deficit/hyperactivity disorder in children and adolescents. American Journal of Psychiatry, 151, 1673-1685.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. Journal of Experimental Psychology, 21, 451-468.

Lavie, N. & Cox, S. (1997). On the efficiency of visual selective attention: Efficient visual search leads to inefficient distractor rejection. Psychological Science, 8, 395-398.

Lavie, N., & Fox, E. (2000). The role of perceptual load in negative priming. Journal of Experimental Psychology: Human Perception and Performance, 26, 1038-1052.

Lavie, N. & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. Perception and Psychophysics, 56, 183-197.

Levy, F. (1991). The dopamine theory of attention deficit hyperactivity disorder (ADHD). Australian and New Zealand Journal of Psychiatry, 25, 277-283.

Littell, R., Milliken, G., Stroup, W., Wolfinger, R. (1996). SAS System for Mixed Models. NC: SAS Institute.

Lou, H., Henriksen, L., & Bruhn, P. (1984). Focal cerebral hypoperfusion in children with dysphasia and/or attention deficit disorder. Archives of Neurology, 41, 825-829.

MacLeod, C.M. (1991). Fifty years of the Stroop effect: An integrative review and reinterpretation of effects. Psychological Bulletin, 114, 376-390.

Maylor, E. & Lavie, N. (1998). The influence of perceptual load on age differences in selective attention. Psychology and Aging, 13, 563-573.

McBurnett, K., Pfiffner, L., & Frick, P. (2001). Symptom properties as a function of ADHD type: an argument for continued study of sluggish cognitive tempo. Journal of Abnormal Child Psychology, 29, 207-213.

McBurnett, K., Pfiffner, L., Willcutt, E., Tamm, L., Lerner, M., Ottolini, Y., Furman, M. (1999). Experimental cross-validation of DSM-IV types of attention-deficit hyperactivity/ disorder. Journal of the America Academy of Child and Adolescent Psychiatry, 38, 17-24.

McCracken, J. (1991). A two-part model of stimulant action on attention deficit hyperactivity disorder in children. Journal of Neuropsychiatry, 3 (2), 201-208.

McIntyre, C., Blackwell, S., & Denton, C. (1978). Effect of noise distractibility on the spans of apprehension of hyperactive boys. Journal of Abnormal Psychology, 6, 483-492.

Miller, J. (1991). The flanker compatibility effect as a function of visual angle, attentional focus, visual transients, and perceptual load: A search for boundary conditions. Perception and Psychophysics, 49, 270-288.

Munoz, D. P., Hampton, K. A., Moore, K. D., & Goldring, J. E. (1999). Control of purposive saccadic eye movements and visual fixation in children with attention-deficit hyperactivity disorder. In W. Becker, H. Deubel, & T. Mergner (Eds.), Current Oculomotor Research: Psychological and Physiological Aspects. New York: Plenum Publishing.

Newman, J. (1998). Psychopathic behavior: An information processing perspective. In Cooke, D., Forth, A., & Hare, R. (Eds.) Psychopathy: Theory, Research, and Implications for Society (pp. 81-104). Kluwer Academic Publishers: Dordrecht, The Netherlands.

Newman, J. Schmitt, W., & Voss, W. (1997). The impact of motivationally neutral cues on psychopathic individuals: Assessing the generality of the response modulation hypothesis. Journal of Abnormal Psychology, 106, 563-575.

Newman, J. & Wallace, J. (1993). Diverse pathways to deficient self-regulation: Implications for disinhibitory psychopathology in children. Clinical Psychology Review, 12, 690-720.

Nigg, J. (2001). Is ADHD an inhibitory disorder? Psychological Bulletin, 5, 571-598.

Nigg, J. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality and a working inhibition taxonomy. Psychological Bulletin, 126, 220-246.

Nigg, J., Hinshaw, S., & Halperin, J. (1996). The continuous performance task in boys with ADHD: Methylphenidate dose response and relations to observed behaviors. Journal of Clinical Child Psychology, 25, 330-340.

Nigg, J.T., Quamma, J.P., Greenberg, M.T., & Kusche, C.A. (1999). A two-year longitudinal study of neuropsychological and cognitive performance in relation to behavioral problems and social competencies in elementary school children. Journal of Abnormal Child Psychology, 27, 51-63.

Nottlemann, E. & Jensen, P. (1995). Comorbidity of disorders in children and adolescents: Developmental Perspectives. Advances in Clinical Child Psychology, 17,

109-155.

Oken, B., Kishiyama, S., & Salinsky, M. (1995). Pharmacologically induced changes in arousal: effects on behavioral and electrophysiologic measures of alertness and attention. Electroencephalography and Clinical Neurophysiology, 95, 359-371.

Ostrander, R., Weinfurt, K., Yarnold, P., & August, G. (1998). Diagnosing attention deficit disorders with the behavioral assessment system for children and the child behavior checklist: Test and construct validity using optimal discriminant classification trees. Journal of Consulting and Clinical Psychology, 66, 660-672.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. Psychological Bulletin, 116, 220-244.

Parasuraman, R. Warm, J. & See, J. (1998). Brain systems of vigilance. In Parasuraman, R. (Ed.) The Attentive Brain (pp. 221-256). MIT Press: Cambridge.

Paus, T., Babenko, V., & Radil, T. (1990). Development of an ability to maintain verbally instructed central gaze fixation in 8 to 10 year old children. International Journal of Psychophysiology, 10, 53-61.

Pelham, W. (1993). Pharmacotherapy for children with attention-deficit hyperactivity disorder. School Psychology Review, 22, 199-27.

Pennington, B. & Ozonoff, S. (1996). Executive functions and developmental psychopathology. Journal of Child Psychology and Psychiatry, 37 (1), 51-87.

Perfetti, C. A. (1985). Reading ability. New York: Oxford University Press.

Plude, D., Enns, J., & Brodeur, D. (1994). The development of selective attention: A life-span overview. Acta Psychologica, 86, 227-272.

Plude, D. & Hoyer, W. (1985). Attention and performance: Identifying and localizing age deficits. In N. Charness (Ed.), Aging and human performance (pp.47-99). New York: Wiley.

Portas, C., Rees, G., Howseman, A., Josephs, O., Turner, R., & Frith, C. (1998). A specific role for the thalamus in mediating the interaction of attention and arousal in humans. The Journal of Neuroscience, 18, 8979-8989.

Posner, M. & Petersen, S. (1990). The attention system of the human brain. Annual Review of Neuroscience, 13, 25-42.

Posner, M., & Raichle, M. (1994). Networks of attention. In Images of Mind (pp. 152-179) New York: Scientific American Library.

Posner, M., Rothbart, M., & Thomas-Thrapp, L. (1997). Functions of orienting in early infancy. In P.J. Lang, R.F. Simons, & M.T. Balaban (Eds.), Attention and orienting: Sensory and motivational processes (pp. 327-345). Mahwah, NJ: Erlbaum.

Proctor, R. & Dutta, A. (1995). Situational influences on skilled performance. In Proctor, R. & Dutta, A. (Eds.), Skill Acquisition and Human Performance (pp.331-362). Thousand Oaks: Sage Publications.

Radosh, A., & Gittelman, R. (1981). The effect of appealing distractors on the performance of hyperactive children. Journal of Abnormal Child Psychology, 9, 179-189.

Reynolds, C. & Kamphaus, R. (1992). Behavior Assessment System for Children: Manual. MN: American Guidance Service, Inc.

Ross, R., Hommer, D., Breiger, D., Varley, C., & Radant, A. (1994). Eye movement task related to frontal lobe functioning in children with Attention Deficit Disorder. Journal of the American Academy of Child and Adolescent Psychiatry, 33, 869-874.

Rothlind, J., Posner, M., & Schaughency, E. (1991). Lateralized control of eye movements in Attention Deficit Hyperactivity Disorder. Journal of Cognitive Neuroscience, 3, 377-381.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. Psychological Review, 103, 403-428.

Satterfield, J., Schell, A., & Nicholas, T. (1994). Preferential neural processing of attended stimuli in attention-deficit hyperactivity disorder and normal boys. Psychophysiology, 31, 1-10.

Sattler, J. (1992). Assessment of Children (3rd Ed.) San Diego: Jerome M. Sattler, Publisher, Inc.

Schachar, R. & Logan, G. (1990). Are hyperactive children deficient in attentional capacity? Journal of Abnormal Child Psychology, 18, 493-513.

Shaffer, D., Fisher, P., Dulcan, M., & Davies, M. (1996). The NIMH diagnostic interview schedule for children version 2.3 (DISC-2.3): Description, acceptability, prevalence rates, and performance in the MECA study. Journal of the American Academy of Child and Adolescent Psychiatry, 35, 865-877.

Sergeant, J., Oosterlaan, J., & van der Meere, J. (1999). Information processing and energetic factors in attention-deficit/hyperactivity disorder. In Quay, H. & Hogan, A., Handbook of Disruptive Behavior Disorders, (pp.75-103). New York: Kluwer Academic.

Servan-Shreiber, D., & Cohen, J. (1992). A neural network model of

catecholamine modulation of behavior. *Psychiatric Annals*, 22, 125-130.

Sharma, V., Halperin, J., Newcorn, J., & Wolf, L. (1991). The dimension of focussed attention: Relationship to behavior and cognitive functioning in children. *Perceptual and Motor Skills*, 72, 787-793.

Solanto, M. (1998). Neuropsychopharmacological mechanisms of stimulant drug action in attention-deficit hyperactivity disorder: A review and integration. *Behavioural Brain Research*, 94, 127-152.

Steinkamp, M. (1980). Relationships between environmental distractions and task performance of hyperactive and normal children. *Journal of Learning Disabilities*, 13, 40-45.

Swanson, J., Lerner, M., March, J. & Gresham, F. (1999). Assessment and intervention of attention-deficit/hyperactivity disorder in the schools. *Pediatric Clinics of North America*, 46, 993-1009.

Tarnowski, K., Prinz, R., & Nay, S. (1986). Comparative analysis of attentional deficits in hyperactive and learning-disabled children. *Journal of Abnormal Psychology*, 95, 341-345.

Taylor, E., Sandberg, S., Thorley, G., & Giles, S. (1991). Developmental and cognitive contrasts. *Institute of Psychiatry Maudsley Monographs*, 33, 51-65.

Treisman, A. & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 97-136.

Treisman, A. (1998). The perception of features and objects. In R. Wright (Ed.) *Visual attention. Vancouver studies in cognitive science* (pp. 26-54), New York: Oxford University Press.

van der Meere, J. (1996). The role of attention. In S.T. Sandberg (ed.) *Monographs in Child and Adolescent Psychiatry* (pp. 111-148). Cambridge: Cambridge University Press.

van der Meere, J. & Sergeant, J. (1988). Focused attention in pervasively hyperactive children. *Journal of Abnormal Child Psychology*, 6, 627-639.

van der Meere, J., Wekking, E., & Sergeant, J. (1991). Sustained attention and pervasive hyperactivity. *Journal of Child Psychology and Psychiatry*, 12, 275-284.

Wechsler, D. (1992). *Wechsler Individual Achievement Test Screener*. San Antonio: Harcourt Brace and Company.

Wechsler, D. (1991). *Wechsler Intelligence Scale for Children—3rd Edition*

Manual. San Antonio: Harcourt Brace.

Weinberg, W. & Harper, C. (1993). Vigilance and its disorders. Behavioral Neurology, 11, 59-78.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. Psychological Bulletin, 120, 272-292.

Wilson, S.P., & Kipp, K. (1998). The development of efficient inhibition: Evidence from directed forgetting tasks. Developmental Review, 18, 86-123.

Winer, B. (1962). Statistical Principles in Experimental Design. NY: McGraw-Hill.

Yantis, S. & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. Journal of Experimental Psychology: Human Perception and Performance, 10, 601-621.

Zacks, R.T. & Hasher, L. (1994). Directed ignoring: Inhibitory regulation of working memory. In D. Dagenbach & T.H. Carr (Eds.) Inhibitory processes in attention, memory, and language (pp. 241-264). San Diego: Academic Press.

Zentall, S. & Zentall, T. (1983). Optimal stimulation: A model of disordered activity and performance in normal and deviant children. Psychological Bulletin, 94, 446-471.

Zentall, S., Zentall, T., & Barak, R. (1978). Distraction as a function of within-task stimulation for hyperactive and normal children. Journal of Learning Disabilities, 9, 540-548.

Ziegler, J., Besson, M., Jacobs, A., Nazir, T. A., & Carr, T. H. (1997). Neural correlates of orthographic and semantic processing: A multitask comparison using event-related potentials. Journal of Cognitive Neuroscience, 9, 758-775.

Table 1

Summary of the perceptual load model of selective attention

Locus of Selection	Early	Late
Level of selection	External world	Internal Representation
Selection based on	Perceptual features	Task demands
Perceptual load	High	Low
Automaticity	Automatic	Effortful
Neuroanatomical Region	Largely posterior	Largely anterior

Table 2

Mean reaction time in ms (SD) to correct target identification and percentage errors (SD) for Study 1

		Adult (n = 20)		4 th Grade (n = 34)	
Distractor	Set Size	Mean RT (SD)	% Errors (SD)	Mean RT (SD)	% Errors (SD)
Incompatible	1	405.59 (93.90)	4.00 (3.67)	771.52 (250.60)	21.72 (14.67)
Neutral	1	379.42 (93.82)	3.00 (2.99)	679.82 (233.79)	14.41 (13.21)
Incompatible	2	469.05 (113.93)	4.33 (3.56)	812.67 (274.20)	23.63 (13.00)
Neutral	2	443.53 (111.10)	3.83 (2.76)	735.97 (260.27)	17.55 (14.16)
Incompatible	4	578.40 (126.22)	7.83 (7.38)	834.54 (281.37)	32.35 (13.60)
Neutral	4	544.32 (106.93)	5.08 (3.27)	806.68 (255.81)	26.27 (13.78)
Incompatible	6	628.46 (125.41)	15.75 (8.63)	872.81 (278.63)	35.15 (12.04)
Neutral	6	634.35 (148.41)	19.08 (6.13)	872.36 (287.36)	35.49 (9.91)

Table 3.

Mean reaction time in ms (SD) to correct target identification and percentage errors (SD) for Study 2

Distractor	Set Size	Adult (n = 22)			2 nd Grade (n = 26)			4 th Grade (n = 23)			6 th Grade (n = 17)		
		Mean RT	% Errors		Mean RT	% Errors		Mean RT	% Errors		Mean RT	% Errors	
Incompatible	1	406.61 (82.43)	3.71 (3.13)		1010.19 (270.42)	15.64 (9.99)		807.42 (167.96)	10.58 (6.77)		706.25 (174.27)	15.10 (9.53)	
Neutral	1	381.50 (78.65)	2.80 (2.08)		909.65 (210.75)	9.74 (6.21)		724.78 (130.88)	7.39 (5.24)		635.54 (143.19)	8.14 (5.36)	
Incompatible	2	492.30 (84.87)	3.94 (4.44)		1093.39 (228.80)	18.14 (8.24)		924.94 (177.91)	14.78 (10.15)		804.25 (177.28)	19.02 (10.74)	
Neutral	2	442.44 (88.25)	3.03 (2.94)		1041.82 (206.58)	11.03 (6.33)		834.80 (148.49)	9.42 (5.36)		748.35 (165.29)	8.33 (6.04)	
Incompatible	4	589.07 (104.12)	7.35 (5.34)		1175.13 (221.73)	30.38 (9.84)		1004.62 (193.28)	19.57 (8.65)		904.49 (199.97)	21.67 (9.97)	
Neutral	4	542.63 (93.63)	5.61 (6.05)		1138.23 (199.18)	24.68 (8.83)		955.86 (163.32)	16.23 (9.79)		858.75 (179.76)	17.06 (9.60)	
Incompatible	6	639.70 (114.93)	12.73 (7.46)		1200.83 (202.89)	34.42 (9.21)		1027.05 (184.36)	29.13 (10.26)		952.25 (236.40)	28.63 (10.68)	
Neutral	6	626.76 (129.22)	18.11 (7.30)		1182.69 (225.39)	35.38 (7.95)		1011.86 (174.46)	29.86 (8.75)		933.73 (244.52)	30.29 (7.25)	

Table 4.

Analysis of variance for child age groups in Study 2

		Reaction Time				Errors		
Source	<i>df</i>	<i>F</i>	η^2	<i>p</i>	<i>F</i>	η^2	<i>p</i>	
Distractor (D)								
2 nd	(1,25)	21.12	0.46	<0.001	36.01	0.59	<0.001	
4 th	(1,22)	28.52	0.56	<0.001	7.85	0.26	0.01	
6 th	(1,16)	14.35	0.47	0.002	10.34	0.39	0.005	
Set Size (S)								
2 nd	(3,75)	32.28	0.56	<0.001	149.54	0.86	<0.001	
4 th	(3,66)	43.67	0.66	<0.001	142.25	0.87	<0.001	
6 th	(3,48)	77.76	0.83	<0.001	87.51	0.84	<0.001	
D X S								
2 nd	(3,75)	2.87	0.10	0.04	5.13	0.17	0.003	
4 th	(3,66)	4.59	0.17	0.006	3.96	0.15	0.01	
6 th	(3,48)	1.61	0.09	0.20	11.88	0.43	<0.001	

Table 5.

Description of groups prior to removal of children with high errors in Study 3

	Control (n = 30)	ADD+H (n = 34)	ADD-H (n = 15)
Percentage Errors	27.49 (10.72)	28.74 (11.51)	29.28 (8.07)
Percentage Hits	71.24 (11.88)	62.90 (18.20)	66.49 (12.43)
Percentage Omissions	1.19 (1.79)	8.08 (15.94)	3.89 (8.26)
Parent BASC hyperactivity index	41.07 (7.43)	71.47 (16.97)	47.47 (9.66)
Parent BASC attention index	43.27 (7.08)	68.88 (8.30)	70.93 (6.68)
Parent Conners global ADHD index	46.00 (5.14)	71.59 (9.39)	70.64 (9.04)
Teacher BASC hyperactivity index	44.38 (3.88)	62.97 (9.85)	54.00 (9.63)
Teacher BASC attention index	43.90 (6.49)	64.19 (8.24)	62.47 (9.72)
Teacher Conners global ADHD index	44.63 (3.59)	68.21 (8.40)	65.15 (12.75)
WIAT reading	105.41 (10.34)	99.91 (18.93)	101.60 (12.09)
Estimated IQ based on 5 subtests	108.83 (15.31)	104.15 (15.08)	101.27 (15.70)
Age in months	121.50 (10.26)	117.41 (10.06)	122.77 (16.16)

Table 6

Description of final groups for study 3

	Control (<u>n</u> = 26)	ADD+H (<u>n</u> = 19)	ADD-H (<u>n</u> = 12)
Parent BASC hyperactivity index	40.62 (6.81)	69.68 (16.10)	46.33 (10.47)
Parent BASC attention index	43.15 (7.22)	68.42 (6.71)	72.42 (6.52)
Parent Conners global ADHD index	46.00 (5.30)	71.37 (8.80)	69.63 (8.30)
Teacher BASC hyperactivity index	43.72 (3.18)	61.63 (9.80)	53.18 (10.02)
Teacher BASC attention index	43.88 (6.60)	62.69 (7.72)	65.42 (5.85)
Teacher Conners global ADHD index	44.50 (3.62)	67.40 (8.19)	66.60 (10.19)
WIAT reading	105.68 (10.54)	103.00 (16.40)	100.92 (13.26)
Estimated IQ based on 5 subtests	109.64 (15.09)	105.26 (17.17)	99.58 (16.32)
Age in months	122.20 (10.32)	119.96 (8.65)	125.23 (16.33)
Comorbid ODD/CD diagnosis (n)	1	8	2
Comorbid Reading Disability (n)	0	1	0
Sex Ratio (M:F)	13:13	17:2	6:6

Table 7.

Mean reaction time in ms (SD) to correct target identification and percentage errors (SD) for Study 3

Distractor	Set Size	Control (n = 26)			ADD-H (n = 12)			ADD+H (n = 18)		
		Mean RT (SD)	% Errors (SD)	Mean RT (SD)	% Errors (SD)	Mean RT (SD)	% Errors (SD)	Mean RT (SD)	% Errors (SD)	Mean RT (SD)
Incompatible	1	758.64 (161.72)	17.08 (10.45)	817.40 (288.85)	22.13 (10.64)	767.34 (244.58)	17.23 (10.12)			
Neutral	1	686.93 (134.87)	12.14 (7.36)	732.45 (270.68)	11.14 (7.92)	702.66 (175.72)	10.55 (6.68)			
Incompatible	2	834.07 (179.59)	23.25 (10.75)	910.41 (318.81)	23.10 (9.69)	845.18 (238.17)	17.48 (9.24)			
Neutral	2	791.91 (172.14)	13.99 (8.13)	835.46 (306.94)	14.33 (7.68)	786.75 (210.82)	13.89 (9.24)			
Incompatible	4	862.81 (180.88)	30.64 (12.21)	909.45 (274.01)	33.68 (10.19)	933.10 (213.30)	24.27 (9.19)			
Neutral	4	849.93 (190.78)	26.65 (11.02)	877.87 (311.17)	25.60 (9.64)	893.11 (225.92)	21.98 (9.03)			
Incompatible	6	869.95 (198.48)	35.59 (11.26)	909.05 (301.81)	38.13 (9.55)	940.69 (215.14)	29.79 (10.91)			
Neutral	6	882.60 (180.40)	34.62 (8.72)	863.48 (261.35)	39.11 (4.69)	925.20 (230.59)	32.08 (9.94)			

	High Load	Low Load
Display size manipulation	a) W X H • V T Y	b) X •
Processing manipulation	c) W N H • V T Y	d) O O O • O N O

Figure 1. Example displays with high and low perceptual loads. The target, located in the circle of letters, can be either an “X” or and “N,” thus requiring subjects to make a forced-choice response. The larger, peripheral letter represents the competing distractor. (a-b): Manipulations of load by changing display sizes, with “a” representing a high load and “b” representing a low load. (c-d): Manipulations of load by changing processing demands, with “c” representing a high load and “d” representing a low load.

a) T L T

b) P L P

Figure 2. Example of stimuli from a flanker-type task. Participants are asked to indicate with a key-press whether the target, located in the center of a line of three letters, is a “T” or an “L.” (a) Incompatible distractors present resulting in slower reaction times to target identification, (b) Neutral distractors present resulting in faster reaction times to target identification. Examples not drawn to scale.

N
.
V

W N H
K . D
V T Y

Figure 3. Example of a two and eight-letter display with a single target (e.g. “N”) and two incompatible flankers from Miller’s (1991) study. Subjects were required to indicate with a key press which one of two possible targets (e.g. an “N” or an “F”) was located in the circle display. The top and bottom halves of the figure are examples of a “low” and “high” load condition, respectively. Flankers are enlarged to account for diminished visual acuity due to increased visual angle from the fixation point. Figure not drawn to scale.

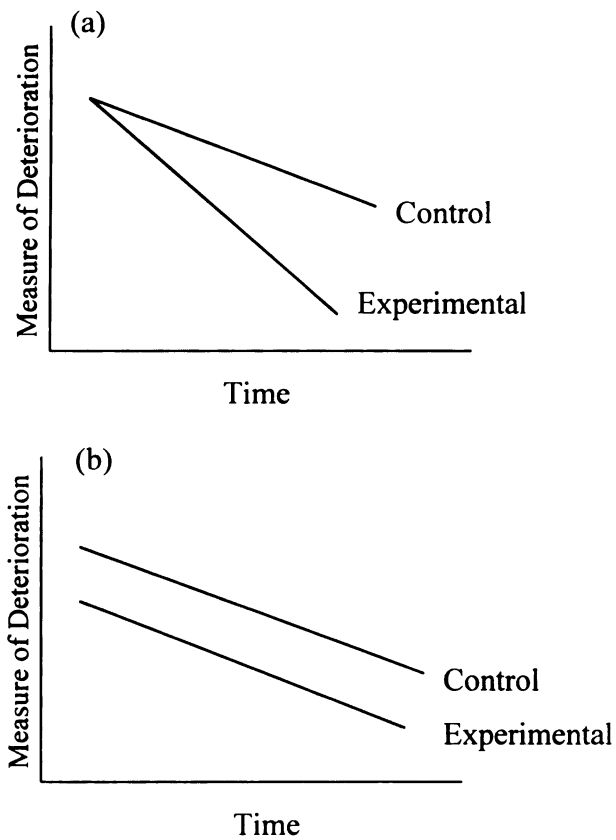


Figure 4. Schematic descriptions of: (a) Pattern of performance indicative of a sustained attentional deficit.(b) Pattern of performance indicative of an arousal deficit, where “lower scores” reflect worse performance on a generic task.

Trial Time Line:

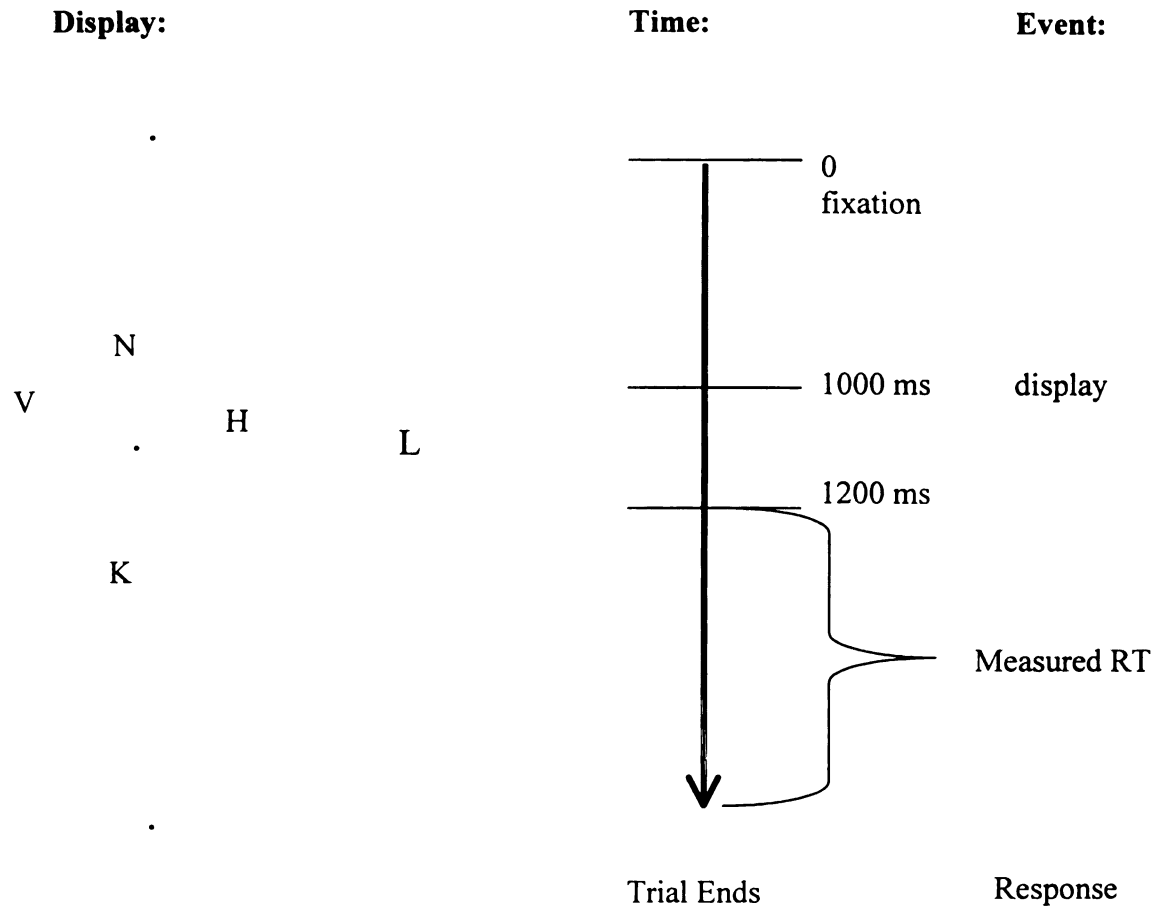


Figure 5. Progression of stimuli for high load (set size = 4) with a neutral distractor (“L”). Children are asked to determine whether the target, either an “X” or an “N” is present in the circle display.

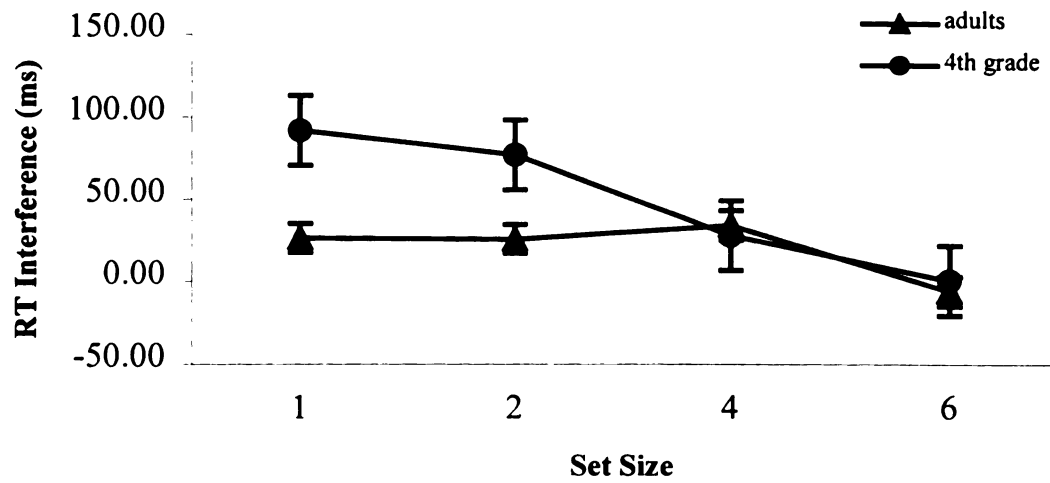


Figure 6. Reaction time interference effects for Study 1. Standard error bars displayed.

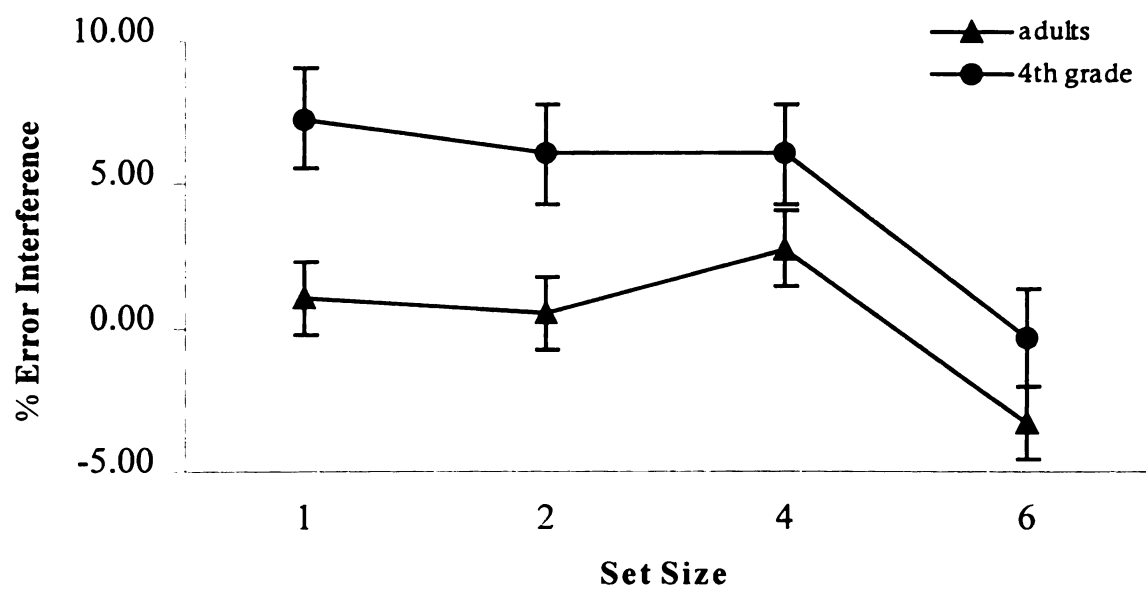


Figure 7. Percentage error interference effects for Study 1. Standard error bars displayed.

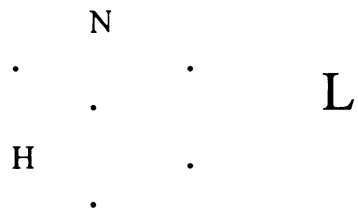


Figure 8. Example display for Study 2 under conditions of low load (set size = 2) with the neutral distractor “L”.

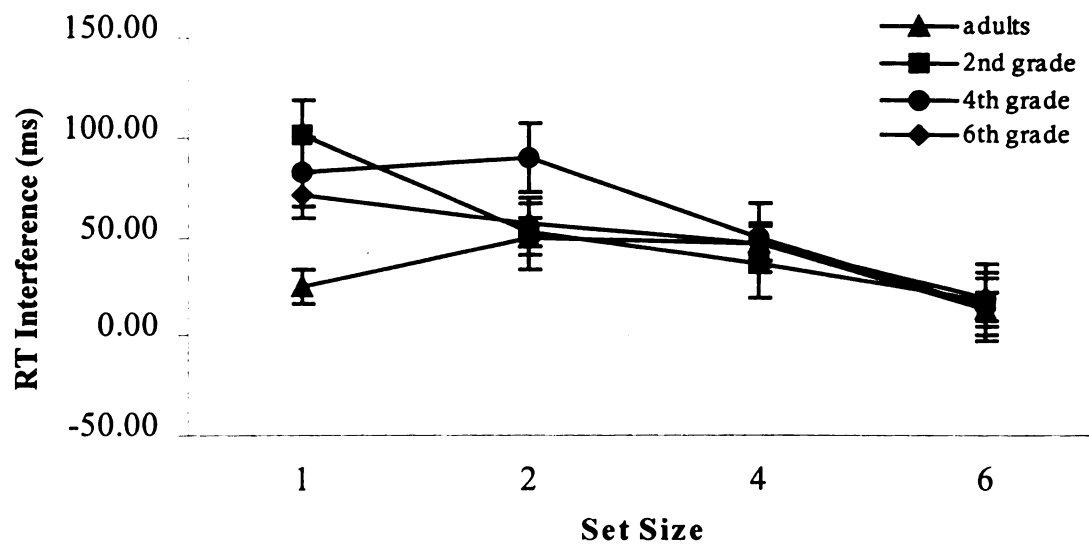


Figure 9. Reaction time interference effects for Study 2. Standard error bars displayed.

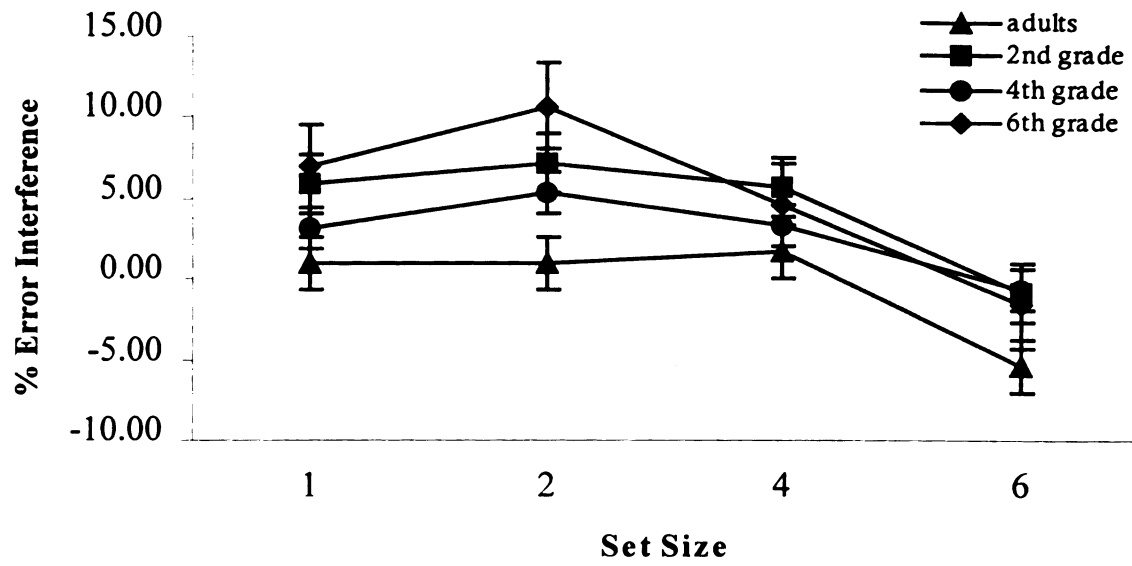


Figure 10. Percentage error interference effects for Study 2. Standard error bars displayed.

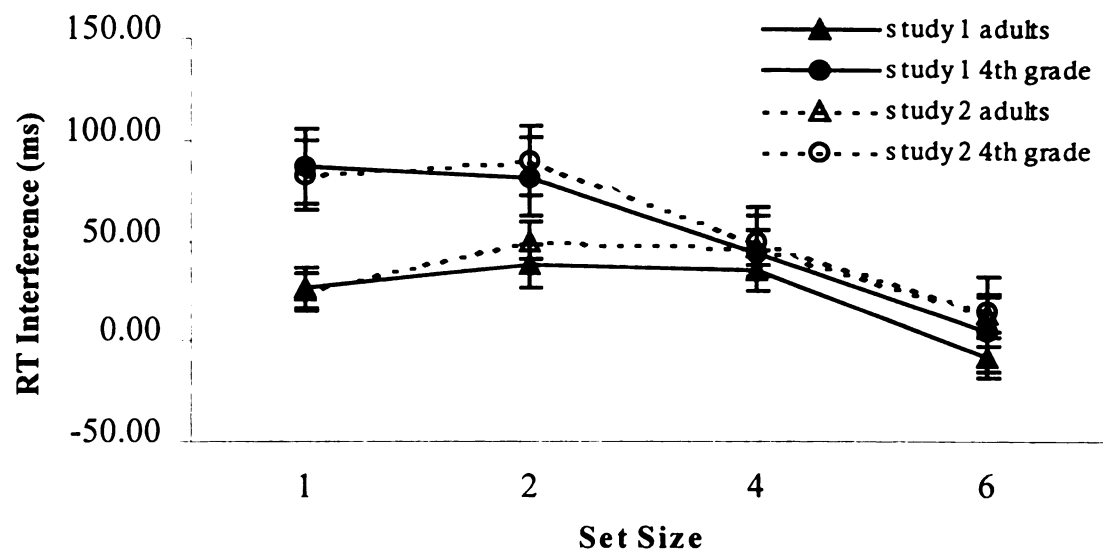


Figure 11. Reaction time interference with and without placemarkers. Standard error bars displayed.

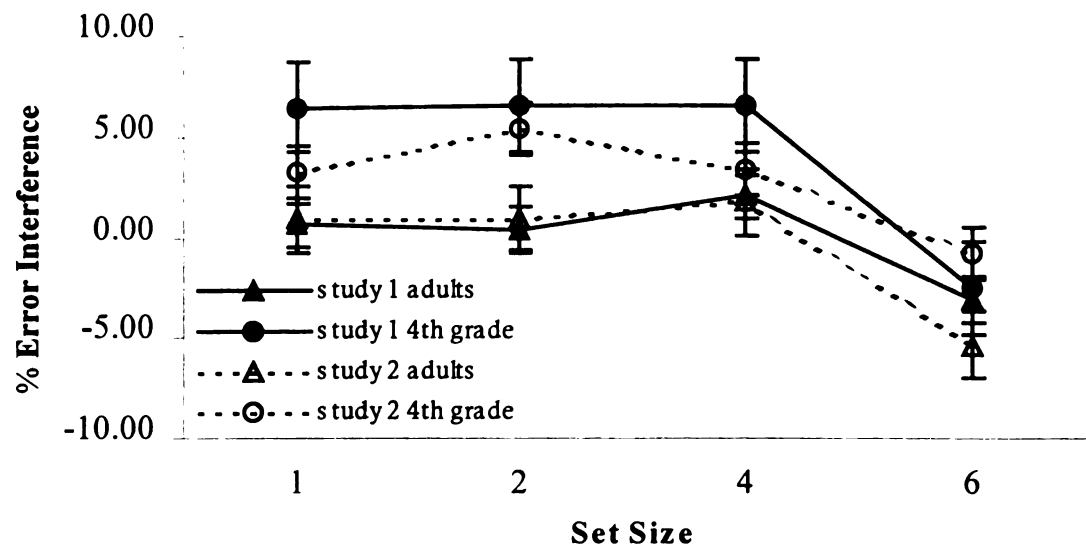


Figure 12. Percentage error interference effects with and without placemarkers. Standard error bars displayed.

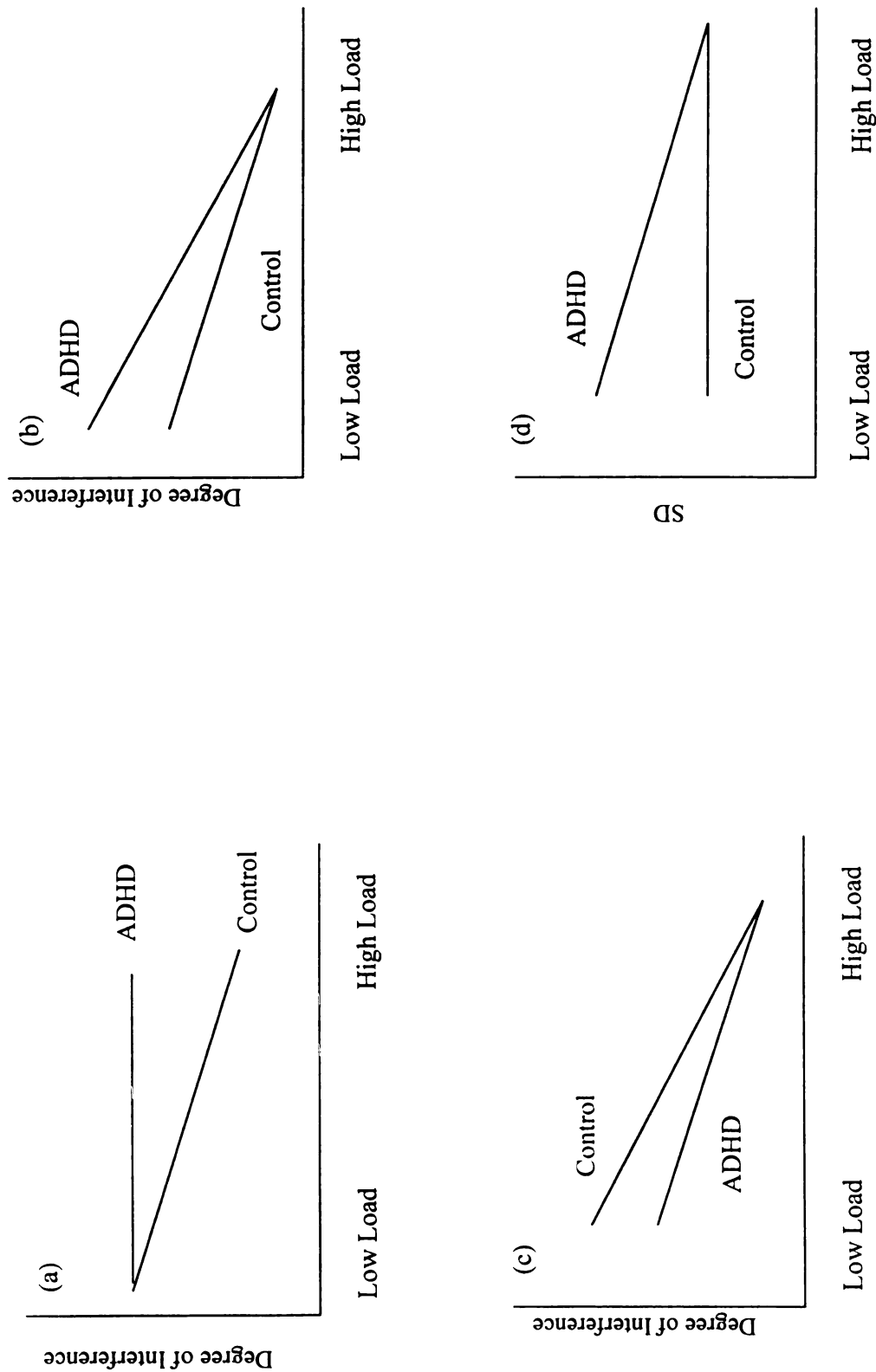


Figure 13. Schematic descriptions of the pattern of results if ADHD represents a deficit in (a) early selective attention, (b) late selective attention, (c) response modulation, or (d) arousal.

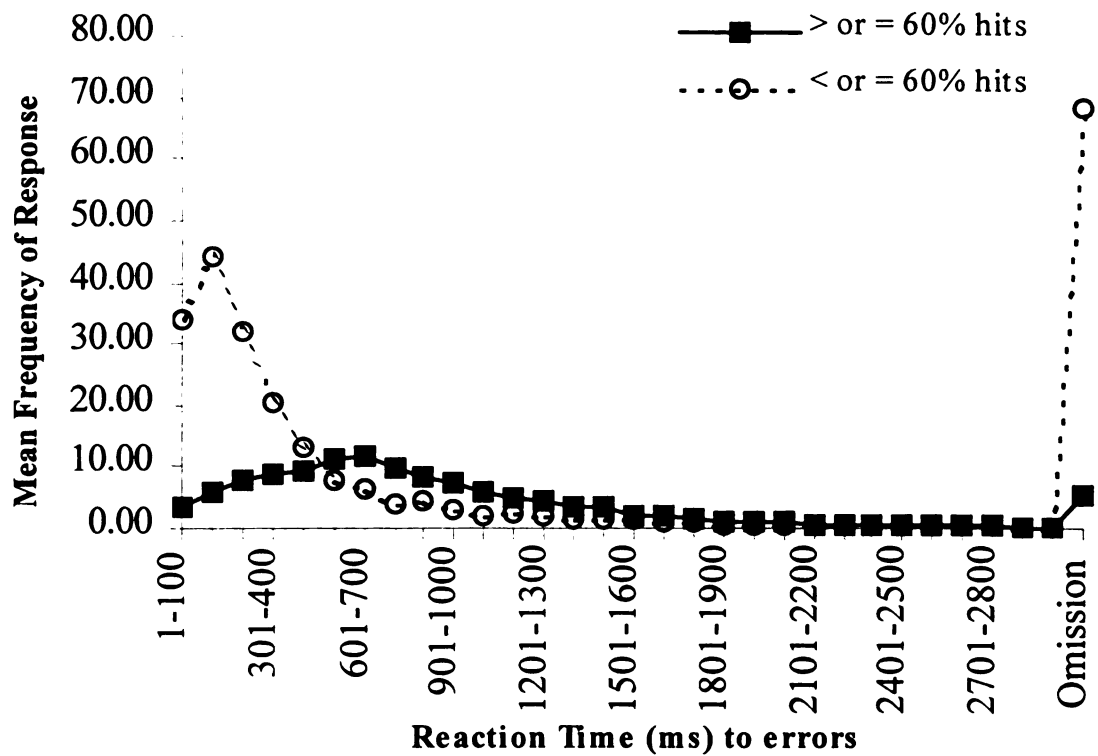


Figure 14. Frequency of responses to incorrect target identification and omission errors occurring in 100 ms intervals for children were and were not able to maintain a 60% accuracy rate, collapsed across diagnostic groups.

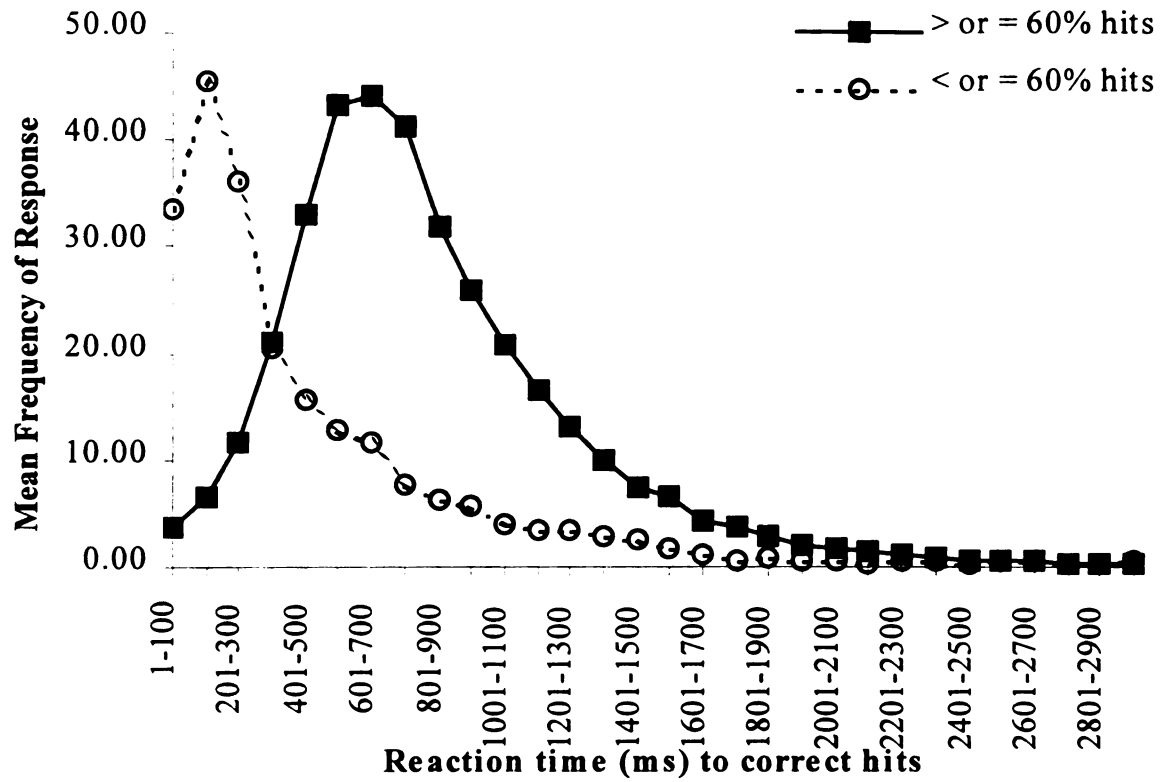


Figure 15. Frequency of responses to correct target identification occurring in 100 ms intervals for children who were and were not able to maintain a 60% accuracy rate, collapsed across diagnostic groups.

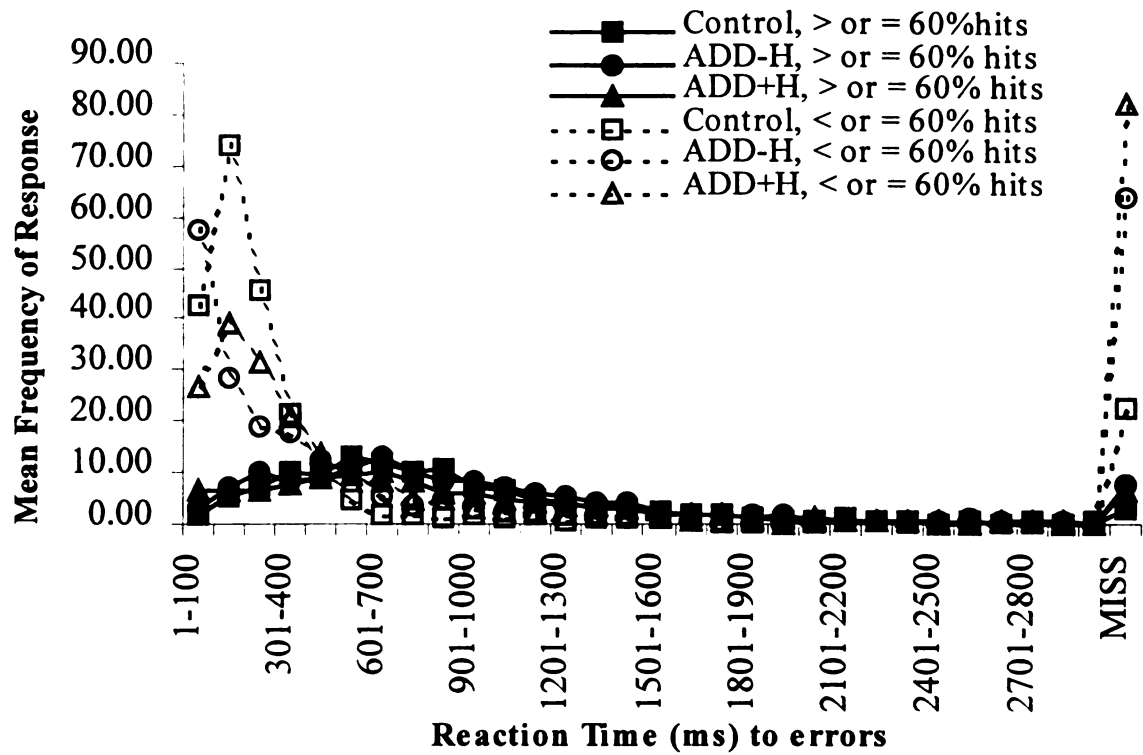


Figure 16. Frequency of response to incorrect target identification and omission errors occurring in 100 ms intervals for children who were and were not able to maintain a 60% accuracy rate, broken down by diagnostic groups.

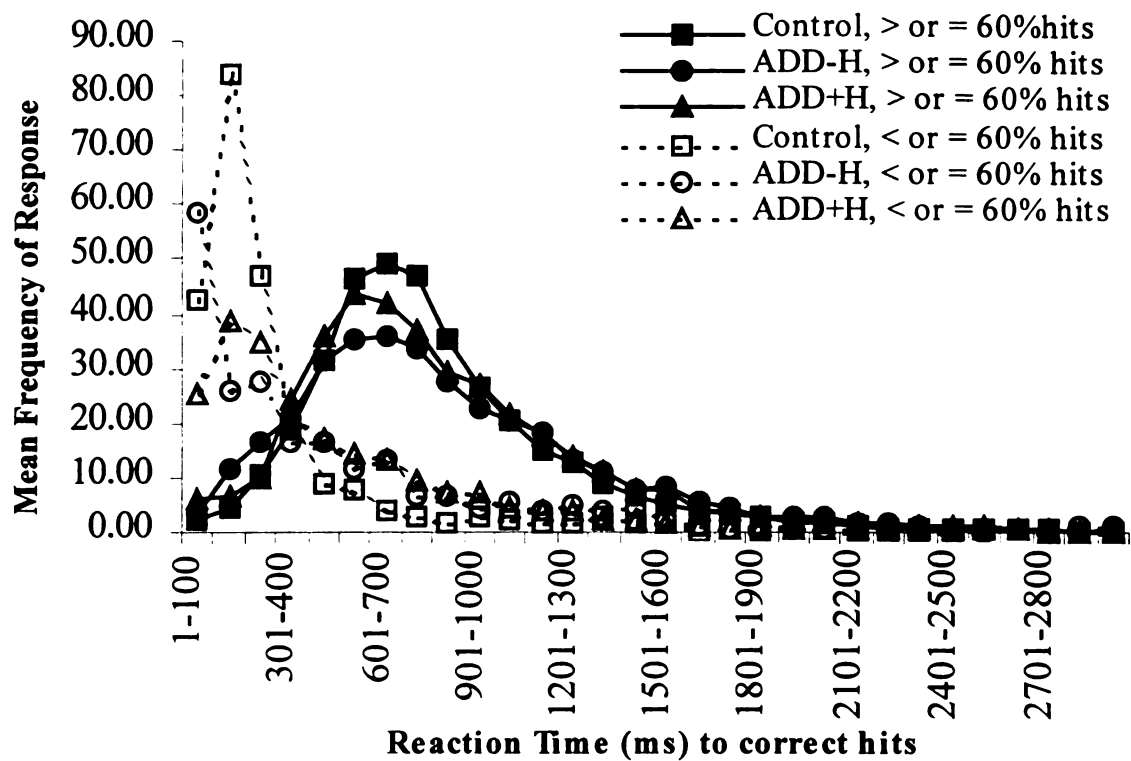


Figure 17. Frequency of response to correct target identification occurring in 100 ms intervals for children who were and were not able to maintain a 60% accuracy rate, broken down by diagnostic groups.

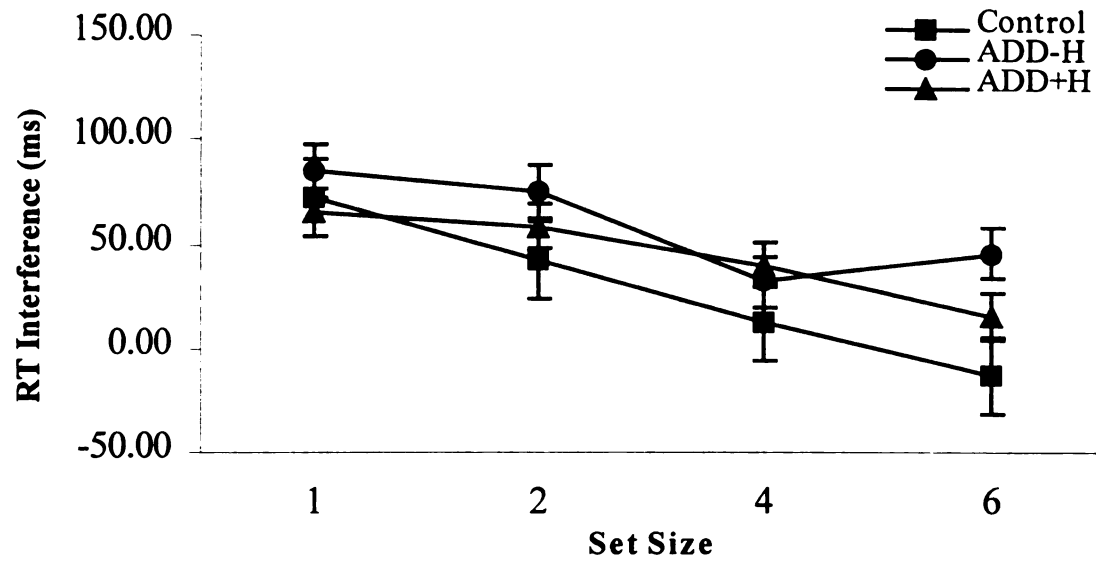


Figure 18. Reaction time interference effects by diagnosis for Study 3. Standard error bars displayed.

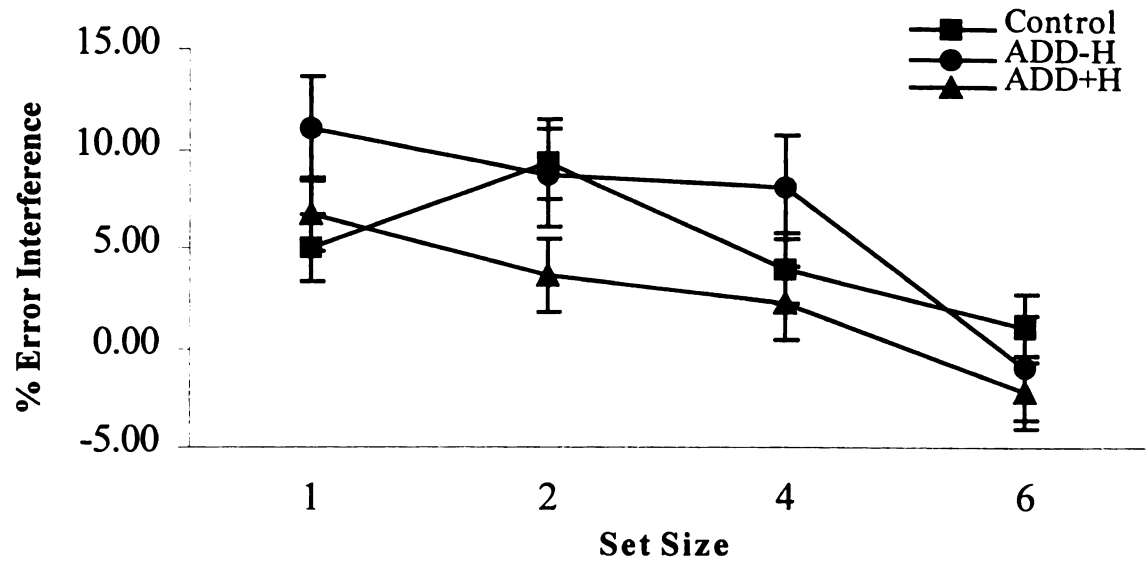


Figure 19. Percentage error interference effects by diagnosis size for Study 3. Standard error bars displayed.

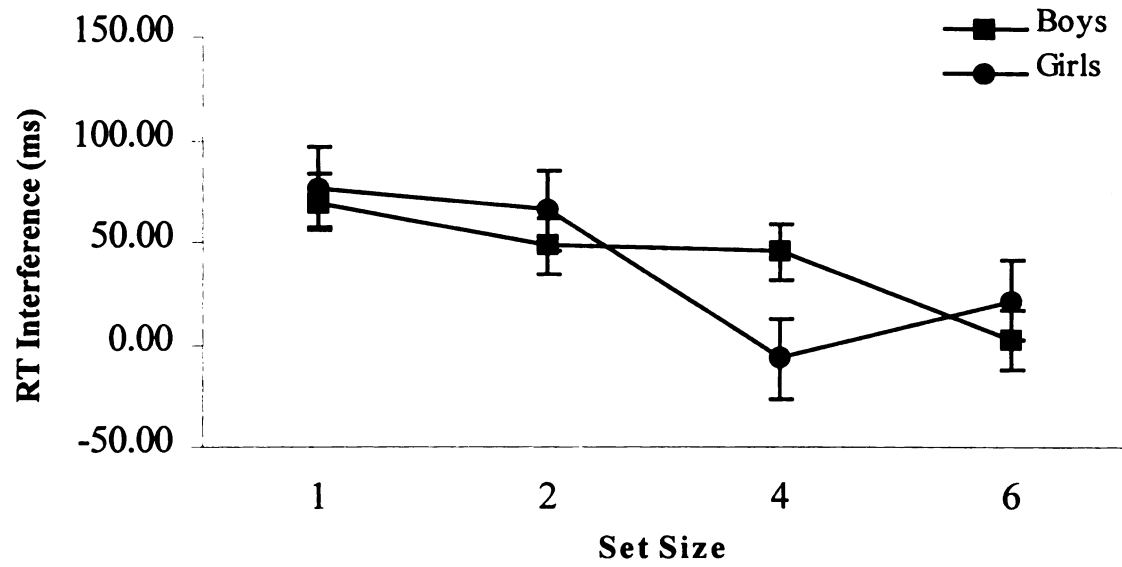


Figure 20. Reaction time interference effects by sex for Study 3. Standard error bars displayed.

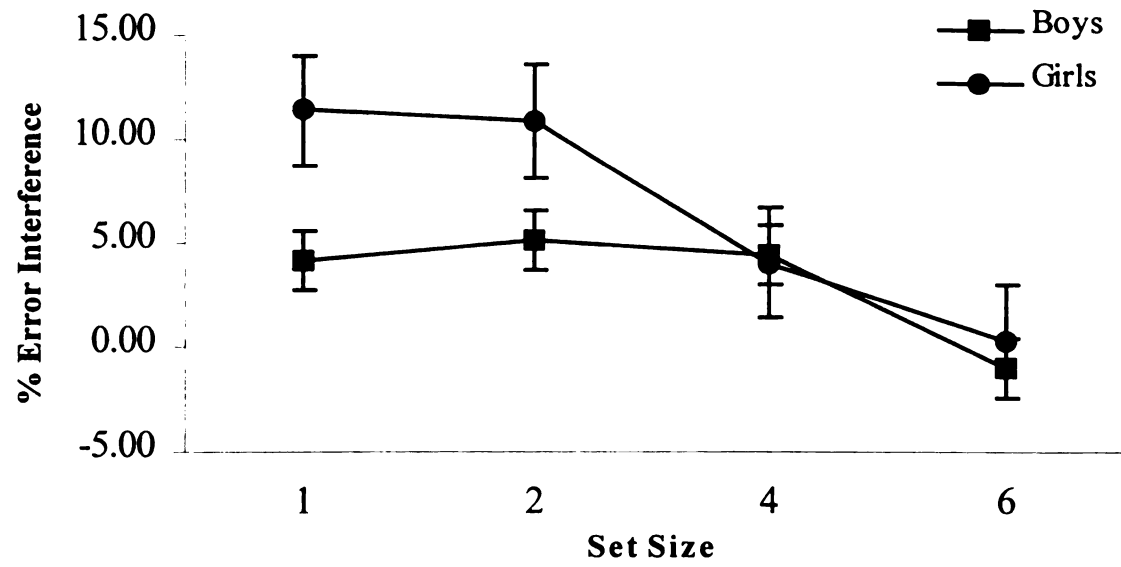


Figure 21. Percentage error interference effects by sex for Study 3. Standard error bars displayed.

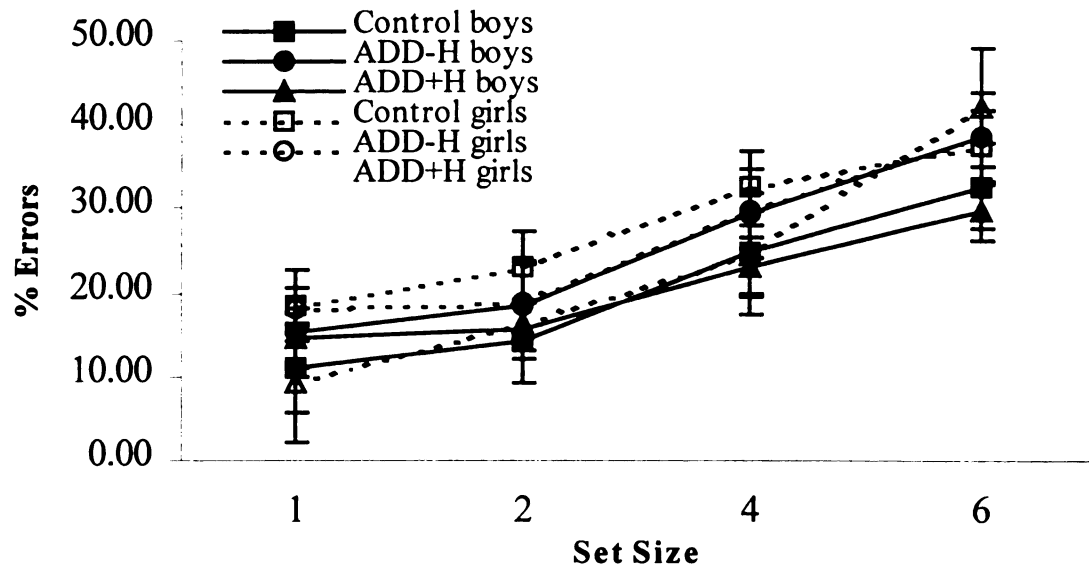


Figure 22. Percentage errors committed by diagnosis and sex for Study 3. Standard error bars displayed.

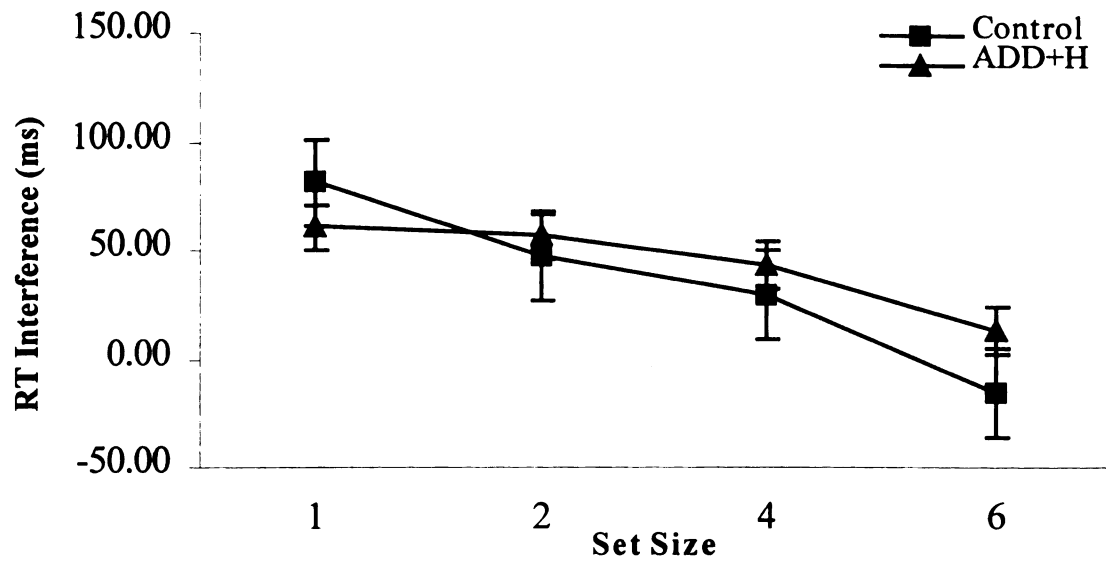


Figure 23. Reaction time interference effects for control and ADD+H boys for Study 3. Standard error bars displayed.

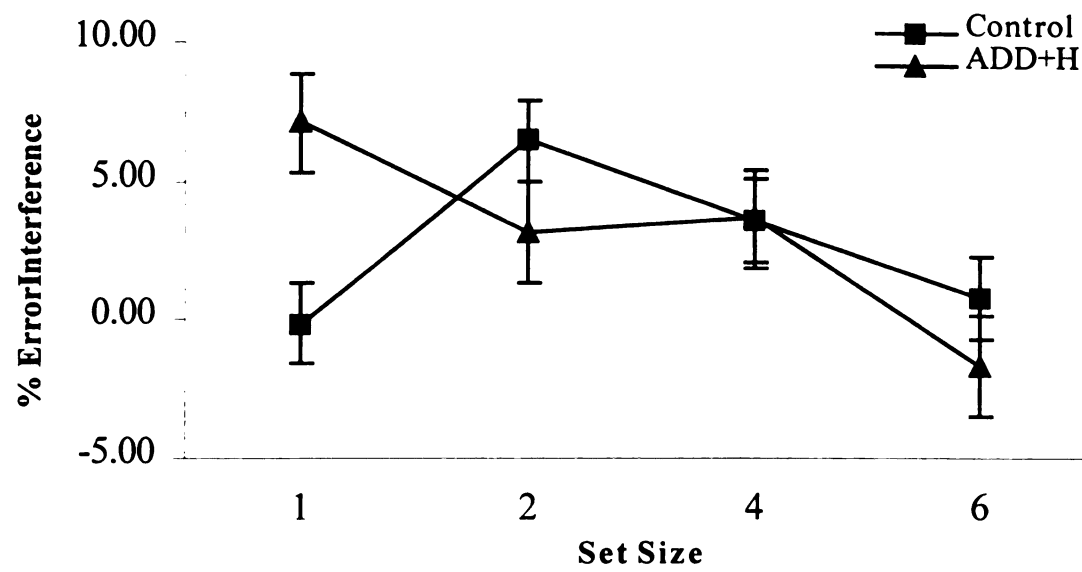


Figure 24. Percentage errors interference effects for control and ADD+H boys for Study 3. Standard error bars displayed.

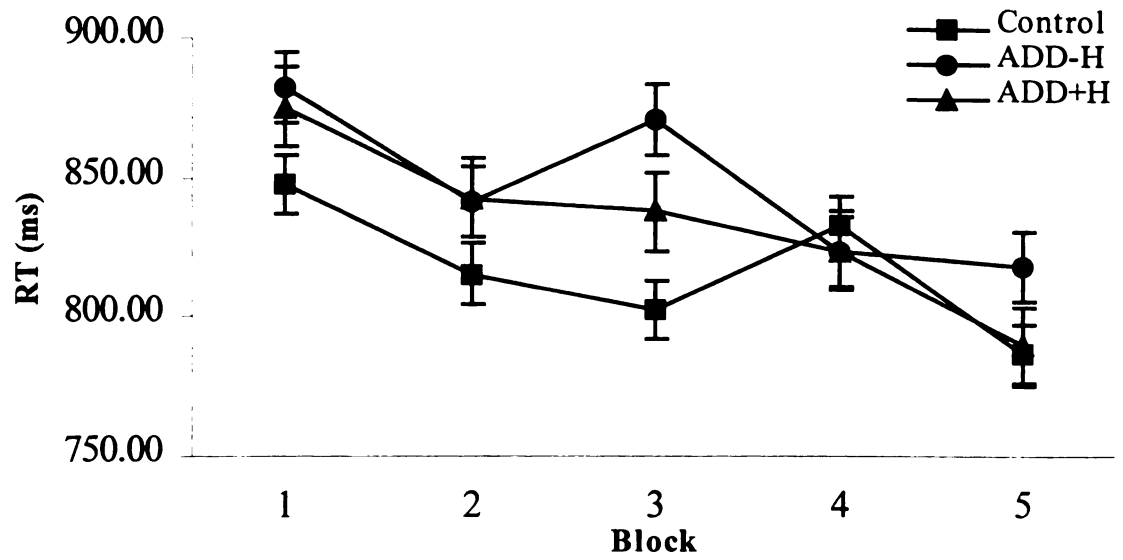


Figure 25. Mean reaction time across time by diagnosis for Study 3. Standard error bars displayed.

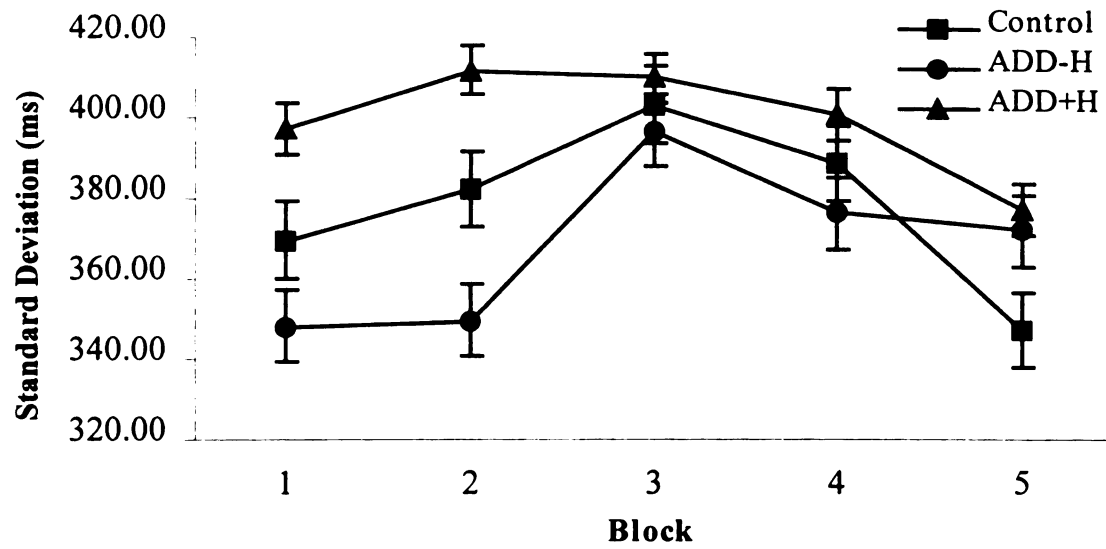


Figure 26. Mean standard deviation across time by diagnosis for Study 3. Standard error bars displayed.

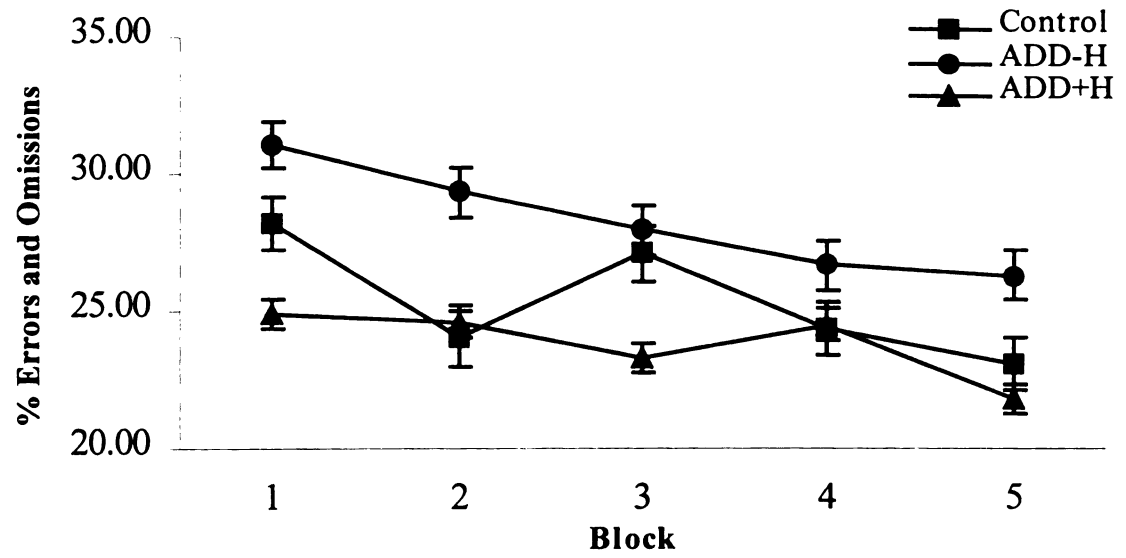


Figure 27. Percentage errors and omissions across time by diagnosis for Study 3. Standard error bars displayed.

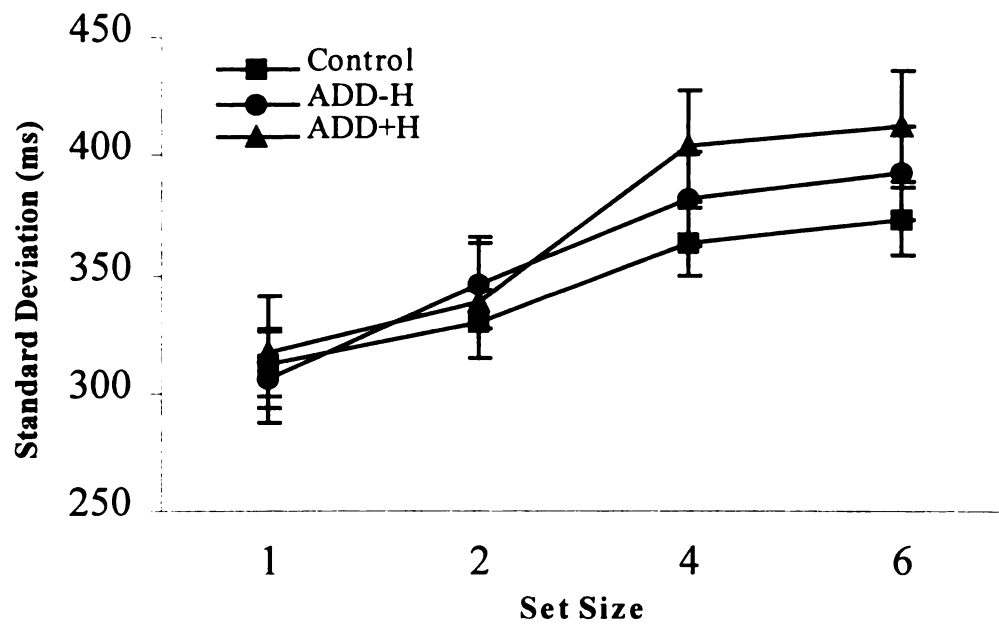


Figure 28. Standard deviation by diagnosis across set size for Study 3. Standard error bars displayed.

APPENDIX I.

Neurochemical and Physiological Evidence of an Inhibitory Deficit in ADHD

Not only have cognitive and neuropsychological performance deficits been noted in children with ADHD, but a number of imaging, EEG, and PET studies have also supported the existence of a frontal lobe disorder in ADHD. That is, children with ADHD perform more poorly than non-ADHD children in tasks measuring response inhibition (Casey, Castellanos, Giedd, Marsh, Hamburger, Schubert, et al., 1997). When observed using MRI techniques, poor performance is correlated with prefrontal cortex, caudate, and globus pallidus volume, predominantly within the right hemisphere (Casey et al., 1997). Likewise, a study of cerebral blood flow found that the white matter of the frontal lobes in children who met DSM-III criteria for attention deficit disorder was hypoperfused, and that this hypoperfusion was partially corrected with the administration of methylphenidate (Lou, Henriksen, & Bruhn, 1983).

More indirectly, a study of corpus callosum morphology in ADHD found that the rostrum and rostral body areas were smaller in children with ADHD and that these results were correlated with parent and teacher report of hyperactive and impulsive behavior (Giedd, Castellanos, Casey, Kozuch, King, Hamburger, Rapoport, 1994). Because the corpus callosum retains topographical consistency with the areas from which the fibers originate, abnormalities in this structure may reflect abnormalities in the areas from which the fibers travel (Giedd et al., 1994). Thus, abnormalities in the rostrum and rostral body of the corpus callosum would suggest abnormalities in the frontal lobe (Giedd et al., 1994). These findings have not been fully replicated, however. In another morphometric study of the corpus callosum in ADHD, smaller corpus callosum area, particularly in the area of the splenium and genu, were found (Hynd, Semrud-Clikeman, Lorys, Novey,

Eliopoulos, & Lyytinen, 1991). Although the genu is located in the rostral section of the corpus callosum, the splenium is located posteriorly.

Because the anterior cingulate is known to be involved with interference control, it may be that this structure is damaged in ADHD. Activation of the anterior cingulate, as measured by fMRI recordings during administration of the Counting Stroop task (a version of the Stroop designed for the fMRI) in adults (aged 18-55) with and without ADHD found that although both groups demonstrated a significant interference effect, the anterior cingulate of ADHD individuals was not activated, in contrast to controls (Bush, Frazier, Rauch, Seidman, Whalen, Jenike, et al., 1999). Indeed, for the ADHD group, no activation in the cingulate cortex was found at all (Bush et al., 1999). This hypofunctionality suggests that individuals with ADHD may compensate for the dysfunction by recruiting more inefficient pathways, and thus perform more poorly, in order to accomplish the same tasks (Bush et al., 1999).

Neurochemically, the dopaminergic system is not only involved with regulating motor behavior (Heilman, Voeller, & Nadeau, 1991), but its connections in the prefrontal cortices (PFC) (Levy, 1991) also make it a vital component in the execution of inhibitory processes. Pharmacologic intervention is the most common form of treatment in ADHD (Pelham, 1993); stimulant medications which affect catecholamine regulation (e.g. methylphenidate) have proven to be effective in the short term treatment of 70-80% of affected children (McCracken, 1991). It is believed that the effectiveness of these forms of intervention come in part from their ability to increase dopaminergic tone in the central nervous system.

In summary, there is a substantial amount of literature supporting the presence of

not only motor interference deficits in ADHD, but also of dysfunctions in the anatomical and neurochemical substrates upon which these processes depend. Furthermore, the utility of pharmacologic treatments which affect neurotransmitter systems involved with the regulation of inhibitory processes are also suggestive of an underlying deficit in inhibition.

APPENDIX II.

Neurochemical and Physiological Evidence of an Arousal Deficit in ADHD

Pharmacological Data. Medications which have the greatest therapeutic benefit in ADHD not only increase the release of dopamine, but also increase adrenergic-mediated inhibition of NE in the LC (McCracken, 1991). Experimentally, improvements on the CPT can be seen following administration of methylphenidate, a NE agonist (Nigg, Hinshaw, & Halperin, 1996). Along with improvements on test performance, methylphenidate has also been found to increase the amplitude and decrease the latency of the P300 wave during EEG recordings (Solanto, 1998). However, neither MAO-A inhibitors (clorgyline) nor mixed MAO-A/MAO-B inhibitors (tranylcypromine), which, like methylphenidate, are also NE agonists, improve performance on the CPT (Levy, 1991). If this system has been correctly understood, the ineffectiveness of some NE agonists, but not others, to improve CPT performance somewhat weakens the argument for an arousal dysfunction.

Physiological Data. In addition to psychopharmacological evidence, the argument for a dysfunctional arousal system in ADHD is also strengthened by the existence of more direct, physiological measures. Such measures (e.g. EEG, auditory evoked responses, and skin conductance measures) have revealed a negative correlation between state of arousal and degree of hyperactivity (Weinberg & Harper, 1993). For example, Cohen and Douglas (1972), in a study of skin conductance orienting responses, found that although children with ADHD did not differ from controls when asked to passively attend repetitive auditory stimuli, when asked to make an active response to the appearance of a light 2, 5, or 10 seconds following the onset of the tone, they did display smaller and less

consistent orienting responses. Thus, control children were able to use the warning tone as an alerting and preparatory stimulus more effectively than children with ADHD (Cohen & Douglas, 1972).

In summary, children with ADHD have consistently demonstrated slower reaction times and more variable performance from the outset of a reaction time task. They additionally respond well to medications which affect the NE system, and important neurochemical in modulating arousal. This data has been used to bolster theories hypothesizing an arousal deficit in ADHD.

APPENDIX III

Behavioral and Cognitive Screening Procedures:

- A. Behavioral Assessment Rating Scales for Children, Parent and Teacher report
(BASC; Reynolds & Kamphaus, 1992),
- B. Conners' Rating Scales—Revised, Parent and Teacher report (Conners'; Conners,
1997)
- C. ADHD rating scale, Parent and Teacher report (DuPaul et al., 1998)
- D. WISC-III
- E. WIAT Screener

MICHIGAN STATE UNIVERSITY LIBRARIES



3 1293 02336 6721