



**JURNAL**

***TRAINING ATTENTION, SELECTIVE ATTENTION,  
SUSTAINED ATTENTION AND ADHD***

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1	Behavioral inhibition, sustained attention, and executive functions constructing a unifying theory of adhd.	- Barkley, R. A	<i>Psychological Bulletin,</i>	1997
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3	Components of attention in children with complex partial seizures with and without ADHD.	- Clikeman, M. S - Wical, B.	<i>Epilepsia</i>	1999
4	Sustained attention in children with specific language impairment (SLI).	- Finneran, D. A. - Francis, A. L. - Leonard, L. B	<i>Speech, language, and Hearing Research</i>	2009
5	Sustained and selective attention boys with attention deficit hyperactivity disorder.	- Hooks, K. - Milich, R. - Lorch, E. P.	<i>Clinical Child Psychology</i>	1994
6	Investigation of a direct intervention for improving attention in young children with adhd.	- Kerns, K. A. - Eso, K. - Thomson, J.	<i>Developmental Neuropsychology</i>	1999
7	The cognitive neuroscience of sustained attention: Where top-down meets bottom-up.	- Sarter, M. - Givens, B. - Bruno, J. P.	<i>Brain Research Reviews</i>	2001
8	Efectiveness of attention-training program.	- Sohlberg, M. M. - Mateer, C. A.	<i>Clinical and Experimental Neuropsychology,</i>	1987

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# Behavioral Inhibition, Sustained Attention, and Executive Functions: Constructing a Unifying Theory of ADHD

Russell A. Barkley  
University of Massachusetts Medical Center

Attention deficit hyperactivity disorder (ADHD) comprises a deficit in behavioral inhibition. A theoretical model is constructed that links inhibition to 4 executive neuropsychological functions that appear to depend on it for their effective execution: (a) working memory, (b) self-regulation of affect–motivation–arousal, (c) internalization of speech, and (d) reconstitution (behavioral analysis and synthesis). Extended to ADHD, the model predicts that ADHD should be associated with secondary impairments in these 4 executive abilities and the motor control they afford. The author reviews evidence for each of these domains of functioning and finds it to be strongest for deficits in behavioral inhibition, working memory, regulation of motivation, and motor control in those with ADHD. Although the model is promising as a potential theory of self-control and ADHD, far more research is required to evaluate its merits and the many predictions it makes about ADHD.

For over 20 years, attention deficit hyperactivity disorder (ADHD) has been viewed as comprising three primary symptoms, these being poor sustained attention, impulsiveness, and hyperactivity (American Psychiatric Association [APA], 1980, 1987; Barkley, 1981; Douglas, 1972, 1983). These behavioral deficits arise relatively early in childhood, typically before the age of 7, and are fairly persistent over development (Barkley, 1990; Hinshaw, 1994; Weiss & Hechtman, 1993). The three major impairments now have been reduced to two, with hyperactivity and impulsivity constituting a single impairment. As a result, three subtypes of the disorder have been proposed in the current clinical view of ADHD offered in the fourth edition of the *Diagnostic and Statistical Manual of Mental Disorders (DSM-IV; APA, 1994)*: predominantly inattentive, predominantly hyperactive–impulsive, and combined types.

ADHD occurs in approximately 3–7% of the childhood population (Barkley, 1990; Szatmari, 1992), with boys being over-represented, on average, approximately 3:1. The disorder persists into adolescence in 50–80% of cases clinically diagnosed in childhood and into adulthood in 30–50% or more of these same cases (Barkley, Fischer, Edelbrock, & Smallish, 1990;

Klein & Mannuzza, 1991; Weiss & Hechtman, 1993). Over development, ADHD is associated with greater risks for low academic achievement, poor school performance, retention in grade, school suspensions and expulsions, poor peer and family relations, anxiety and depression, aggression, conduct problems and delinquency, early substance experimentation and abuse, driving accidents and speeding violations, as well as difficulties in adult social relationships, marriage, and employment (Barkley, 1990; Barkley, Fischer, et al., 1990; Barkley, Guevremont, Anastopoulos, DuPaul, & Shelton, 1993; Barkley, Murphy, & Kwasnik, 1996, in press; Biederman, Faraone, & Lapey, 1992; Hinshaw, 1994; Murphy & Barkley, in press; Nadeau, 1995; Weiss & Hechtman, 1993). Most of these developmental risks may be exacerbated by the presence of comorbid aggression–conduct problems (Barkley, Fischer, et al., 1990; Barkley et al., 1993; Hinshaw, 1987, 1992, 1994). Treatments for ADHD often include parent, family, and teacher counseling about the disorder; parent and teacher training in behavior management techniques; special education resources; and psychoactive medications (Barkley, 1990).

The history of ADHD has been reviewed elsewhere (Barkley, 1990; Schachar, 1986; Werry, 1992), so I only briefly consider it here. Initially, the symptoms were thought to arise out of poor volitional inhibition and defective moral regulation of behavior (Still, 1902). Later, problems with hyperactivity were thought to be the major feature of the disorder (Chess, 1960; Laufer & Denhoff, 1957). Eventually, Douglas (1972; Douglas & Peters, 1979) stressed an equal if not greater role for poor sustained attention and impulse control in the disorder. She subsequently amended her view to include four major deficits: (a) poor investment and maintenance of effort, (b) deficient modulation of arousal to meet situational demands, (c) a strong inclination to seek immediate reinforcement, along with (d) the originally proposed difficulties with impulse control (Douglas, 1980, 1983). Douglas (1988) later concluded that these four deficiencies arise from a more central impairment in self-regulation in ADHD.

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Russell A. Barkley, Departments of Psychiatry and Neurology, University of Massachusetts Medical Center.

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Correspondence concerning this article should be addressed to Russell A. Barkley, Department of Psychiatry, University of Massachusetts Medical Center, 55 Lake Avenue North, Worcester, Massachusetts 01655. Electronic mail may be sent via Internet to rbarkley@bangate1.ummed.edu.

Others have argued that the cognitive deficits in ADHD may best be understood as a motivational deficit (Glow & Glow, 1979) or as arising from poor stimulus control, a diminished sensitivity to reinforcement, or deficient rule-governed behavior (Barkley, 1981, 1989; Haenlein & Caul, 1987). Such views, however, were not widely adopted, nor did they serve as an impetus to much new research. Zentall (1985) set forth an optimal stimulation theory of ADHD, arguing that the hyperactivity arises from low levels of arousal and serves to maintain an optimal arousal level; the hyperactivity, in a sense, is a form of self-stimulation. More recently, researchers theorizing on ADHD have emphasized poor behavioral inhibition as the central impairment of the disorder (Barkley, 1990, 1994; Quay, 1988a; Schachar, Tannock, & Logan, 1993; Schachar, Tannock, Marriott, & Logan, 1995).

In keeping with this trend, in this article I attempt to provide a unifying model of ADHD that is founded on prior theories of the neuropsychological functions of the brain's prefrontal lobes. Poor behavioral inhibition is specified as the central deficiency in ADHD. The model then sets forth a linkage between response inhibition and four executive functions that depend on such inhibition for their own effective performance. These four functions serve to bring behavior under the control of internally represented information and self-directed actions. By doing so, the four functions permit greater goal-directed action and task persistence. The model provides a more comprehensive account of research findings on the cognitive deficits associated with ADHD than does the current clinical view, which sees ADHD as primarily an attention deficit. The model also predicts many additional deficits likely to be associated with ADHD that have received little or no testing in research. Such predictions provide avenues for attempts at falsification of the model and point to new areas for scientific investigation.

The goal here is admittedly ambitious, perhaps overly so, because the model I propose may be potentially misconstrued as a "theory of everything." Yet its boundaries are generally circumscribed to the domain of self-regulation in developmental psychology or executive functions in neuropsychology. Albeit a broad domain, it is not unlimited. It can be readily distinguished from other major domains of neuropsychological functioning such as sensation and perception, memory, language, and the spatial, sequential, emotional, and motivational domains, among others. The model may overlap with these other domains, however, to the extent that self-regulation may affect them. Before I proceed to discuss the origins of the model, its components, and its extension to ADHD, the ambitiousness of this undertaking demands a justification for why a new model of ADHD is even necessary at this time.

### The Need for a New Model of ADHD

A new theory of ADHD is needed for a number of reasons. First, current research on ADHD is nearly atheoretical, at least in regards to its basic nature. That research is mainly exploratory and descriptive, with two exceptions. One is Quay's (1988a, 1988b, 1996) use of Gray's (1982) neuropsychological model of anxiety to explain the origin of the poor inhibition seen in ADHD. This Quay-Gray model states that the impulsiveness

arises from an underfunctioning of the brain's behavioral inhibition system. That system is said to be sensitive to signals of conditioned punishment, and the model predicts that those with ADHD should prove less sensitive to such signals, particularly in passive avoidance paradigms (Milich, Hartung, Martin, & Haigler, 1994; Quay, 1988b). The second exception is the work of Sergeant and van der Meere (1988; Sergeant, 1995a, 1995b, 1996; van der Meere, in press; van der Meere, van Baal, & Sergeant, 1989), who successfully used information-processing theory and its associated energetic model (arousal, activation, and effort) for isolating the central deficit(s) in ADHD within that paradigm (Sergeant, 1995b). However, this approach does not set forth a theory of ADHD; like the Quay-Gray theory, it makes no effort at large-scale theory construction so as to provide a unifying account of the various cognitive deficits associated with ADHD. Apart from these exceptions, the current clinical view of ADHD (i.e., that of the *DSM-IV*) and the vast majority of current research being conducted on its nature are not theory driven (Taylor, 1996). One sign of advancement in a scientific field is that its research becomes so driven. This synthesis is an attempt to move research on ADHD further along in that direction.

Douglas's (1980) earlier model of ADHD is not actually a theory; it is mainly descriptive and was arrived at inductively from a review of the extant research findings on ADHD in which Douglas (1980, 1983; Douglas & Peters, 1979) discerned a pattern among the findings consistently noted in this field. That pattern comprised the four deficiencies noted earlier. Although it was tremendously helpful at the time, such pattern discernment remains at a descriptive level, albeit one more synthetic than prior efforts at conceptualizing ADHD. But it is neither explanatory nor, more important, predictive of new hypotheses that are testable. It still begs the question of just how the pattern itself is to be explained. Appealing to the construct of self-regulation (Douglas, 1988) is a step in the right direction but is of only modest help unless self-regulation itself is defined and the manner in which it leads to the four impairments is explained. Both the pattern and the later use of self-regulation as an explanatory construct by Douglas fit well within the model developed below. This theory, however, goes much further by providing the needed definition of self-regulation, articulating the cognitive components that contribute to it, specifying the primacy of behavioral inhibition within the theory, and setting forth a motor control component to ADHD. Most important, the model reveals a diversity of new, untested, yet testable predictions about cognitive and behavioral deficits deserving of study.

A second reason why a theory of ADHD is sorely needed is that the current clinical view of ADHD (i.e., that of the *DSM-IV*), being purely descriptive of two behavioral deficits (inattention and hyperactivity-impulsivity), also cannot readily account for the many cognitive and behavioral deficits associated with ADHD that are reviewed later in this article. To account for such findings, any model must fulfill at least five key requirements: (a) It must explain why an actual deficit in attention in children with ADHD has not been found (Schachar et al., 1993, 1995; Sergeant, 1995a, 1995b; van der Meere, in press; van der Meere & Sergeant, 1988a, 1988b, 1988c), even though research on parent and teacher ratings of ADHD repeatedly identifies a

factor of "inattention"; (b) it must explain the link between poor behavioral inhibition (hyperactivity-impulsivity) and this sister impairment of inattention, or whatever this symptom turns out to be; (c) it also must link these two constructs with executive or metacognitive functions because most, if not all, of the cognitive deficits associated with ADHD seem to fall within the realm of self-regulation or executive functions (Barkley, 1995; Denckla, 1994, 1995; Douglas, 1988; Grodzinsky & Diamond, 1992; Pennington & Ozonoff, 1996; Pennington, Grossier, & Welsh, 1993; Seidman et al., 1995; Torgesen, 1994; Welsh, Pennington, & Grossier, 1991; Weyandt & Willis, 1994); (d) it must ultimately connect the literature on ADHD with the larger literatures of developmental psychology and developmental neuropsychology as they pertain to self-regulation and executive functions if it is to argue that ADHD arises from a disruption in developmental processes; and (e) it must be useful as a scientific tool and must make explicit predictions about new phenomena that will both drive research initiatives and provide a means of falsifying the theory.

A third reason for a new model of ADHD is that the current view treats the subtypes of ADHD as sharing qualitatively identical deficits in attention while differing only in the presence of hyperactive-impulsive symptoms. As noted above, it is doubtful that the problems with inattention associated with hyperactive-impulsive behavior lie in the realm of attention, whereas those seen in the predominantly inattentive type of ADHD appear to do so. A digression is necessary here. The predominantly hyperactive-impulsive type actually seems to be a developmental precursor to the combined type. In the field trial for ADHD in the *DSM-IV*, this hyperactive-impulsive type was chiefly found among preschool children (Applegate et al., 1995). In contrast, the combined type was far more represented in school-aged children, as was nearly the entire sample of the inattentive type. This relationship of ADHD type to the ages associated with it likely arises from a simple observation made in prior studies. The hyperactive-impulsive behavior pattern seems to emerge first in development, during the preschool years, whereas the symptoms of inattention associated with it appear to have their onset several years later, at least according to parental reports (Hart, Lahey, Loeber, Applegate, & Frick, 1995; Loeber, Green, Lahey, Christ, & Frick, 1992). Moreover, the types of problems with inattention seen in the predominantly inattentive type appear to have their onset even later than those that would eventually be associated with hyperactive-impulsive behavior (Applegate et al., 1995).

Returning, then, to the start of this digression, it appears that the predominantly inattentive type may not, in fact, have its impairment in the same form of attention as that found in the other two types (see Barkley, 1990; Barkley, Grodzinsky, & DuPaul, 1992; Goodyear & Hynd, 1992; Hinshaw, 1994; and Lahey & Carlson, 1992, for reviews). Research on the inattentive subtype suggests that symptoms of daydreaming, "spacing out," being "in a fog," being easily confused, staring frequently, and being lethargic, hypoactive, and passive are more common (Barkley, DuPaul, & McMurray, 1990; Lahey & Carlson, 1992). This type of ADHD has a deficit in speed of information processing, generally, and in focused or selective attention, specifically (Goodyear & Hynd, 1992; Lahey & Carlson, 1992).

The deficit in the combined type of ADHD has been characterized as being in the realm of sustained attention (persistence) and distractibility. If this distinction is valid, the present clinical view of ADHD may be clustering into a single set of disorders what are, in reality, two qualitatively different disorders. Such a distinction would also argue that children with ADHD combined type who may develop the inattentive type as they get older (because of reductions in hyperactive behavior) are not actually changing types of ADHD at all. The type of inattention that they continue to manifest (lack of persistence and distractibility) is still qualitatively different from the inattention manifested by children classified as the inattentive type. Any new theory of ADHD needs to address this emerging distinction. The model presented here provides a means of testing this dissociation between types of inattention by using functional neuroimaging methods along with measures of the executive functions whose deficiencies are linked in this model to the hyperactive-impulsive types of ADHD.

#### Clarification of Terms and Assumptions

The term *ADHD* is used here to refer only to that subgroup of this population previously identified as hyperactive (Chess, 1960), hyperkinetic (APA, 1968), attention deficit disorder with hyperactivity (APA, 1980), ADHD (APA, 1987), or, more recently, ADHD-combined type and hyperactive-impulsive type (APA, 1994). In this article, ADHD and the model of it developed here do not refer to that subgroup whose chief problem is inattention alone (predominantly inattentive type).

The model set forth below presumes that the essential impairment in ADHD is a deficit involving response inhibition. This deficit leads to secondary impairments in the four neuropsychological abilities that are partially dependent on inhibition for their effective execution. These secondary impairments then lead to decreased control of motor behavior by internally represented information and self-directed action. One consequence of this hierarchical relationship is that improvement or amelioration of the inhibitory deficit should result in improvement or normalization in the four executive functions that depend on it and also in improved motor control. Another consequence is that this successive chain of impairments creates the appearance of poor sustained attention in those with ADHD. However, this inattention actually represents a reduction in the control of behavior by the internally represented information contributed by these four executive functions. That information permits the tracking of the adherence of behavior to it (i.e., rules, plans, intentions, goals, time, etc.), thus creating goal-directed persistence.

Behavioral inhibition refers to three interrelated processes: (a) inhibition of the initial prepotent response to an event; (b) stopping of an ongoing response, which thereby permits a delay in the decision to respond; and (c) the protection of this period of delay and the self-directed responses that occur within it from disruption by competing events and responses (interference control). It is not just the delay and the self-directed actions within it that are protected but also the eventual execution of the goal-directed responses generated from those self-directed actions (Bronowski, 1977; Fuster, 1989). The *prepotent response* is defined as that response for which immediate rein-

forcement (positive or negative) is available or has been previously associated with that response. The inhibitory process involved in interference control may be separable from that involved in the delay or cessation of a response. Nevertheless, the previous neuropsychological models on which the present one is based clustered these processes together. That fact, along with research reviewed below which suggests that all three inhibitory activities are impaired in ADHD, has led to their treatment here as a single construct.

This definition of inhibition is not exactly the same as that used by Kagan, Reznick, and Snidman (1988) to study shy (inhibited) and sociable (uninhibited) children. In Kagan et al.'s research, uninhibited behavior is defined by reactions to social settings involving unfamiliar people in which children are consistently sociable, talkative, and affectively spontaneous. It is the polar opposite of shyness (clinging, quiet, timid, and withdrawn behavior). In contrast, inhibition is assessed by performance on cognitive and behavioral tasks that require withholding of responding, delayed responding, cessation of ongoing responses, and resisting distraction or disruption by competing events. The social characteristics of children with low social inhibition in Kagan et al.'s research may be similar to some of the behavioral effects in the model developed here. The two concepts and their correlates, however, do not appear to map precisely onto each other, nor do they seem to predict the same outcomes.

For instance, Caspi and Silva (1995) found that separate dimensions of temperament for undercontrolled behavior (impulsive, emotionally reactive, easily frustrated, and overactive) and for socially confident behavior (sociable, talkative, and eager to explore unfamiliar contexts) could be extracted from ratings of 3-year-olds. These two dimensions predicted very different personality characteristics in adulthood, with the former associated with more maladaptive behavior than the latter. The undercontrolled behavior pattern seems more closely related to the poor inhibition in the present model than is the socially confident pattern, which resembles Kagan et al.'s (1988) sociable (uninhibited) children.

This is hardly the first article to argue that behavioral inhibition is a central impairment in ADHD. Distinctive of the model to be offered here, however, is its linkage of this deficiency in inhibition to the disruption of five other neuropsychological abilities that depend on inhibition for their efficient execution. Four of these abilities are critical for self-regulation and goal-directed persistence, so they are called *executive functions* here. ADHD is believed to disrupt these executive functions because the first executive, self-regulatory act must be inhibition of responding. Such inhibition permits a delay in the decision to respond that is used for further self-directed, executive actions. Those actions affect the decision to respond and control the eventual responses these executive functions generate.

This is not to say that behavioral inhibition directly causes these executive or self-directed actions to occur. However, it does set the occasion for their performance by providing the delay necessary for them to occur. These four executive functions, therefore, should be viewed as neuropsychological systems separate from the behavioral inhibition system yet hierar-

chically (or pyramidally) perched on it to assist in self-regulation.

*Self-regulation* is any response, or chain of responses, by the individual that serves to alter the probability of the individual's subsequent response to an event and, in so doing, functions to alter the probability of a later consequence related to that event (Kanfer & Karoly, 1972; Skinner, 1953). These self-directed behaviors need not be publicly observable, although it is likely that in early development many of them are. Over development, they may become progressively more private, or internal-cognitive, in form. The development of internalized, self-directed speech, to be discussed later, may serve to exemplify this process. Although eventually private, these actions remain essentially self-directed forms of behavior. The term *executive function* refers to these mainly private (cognitive) self-directed actions that contribute to self-regulation. So defined, the term incorporates most of the attributes often ascribed to it by others (Denckla, 1994; Stuss & Benson, 1986; Torgesen, 1994; Welsh & Pennington, 1988), including (a) self-directed actions; (b) the organization of behavioral contingencies across time; (c) the use of self-directed speech, rules, or plans; (d) deferred gratification; and (e) goal-directed, future-oriented, purposive, or intentional actions.

A conflict between the immediate and distal consequences of an act may be critical for identifying those circumstances that serve to initiate inhibition and self-regulation (Kanfer & Karoly, 1972). Inhibition and its related executive functions may be most obvious (and most needed) when a delay of a consequence is imposed in a task, when a conflict is confronted between the immediate and delayed consequences of a response, or when a problem arises that requires generating a novel response to resolve it. Time, conflicts in temporally related outcomes, or novelty of a response, therefore, may serve as initiating events for these executive functions. The future consequence is not actively influencing this process because it has not yet occurred. Instead, conditioned signals of punishment from experiences and prior socialization may be the determinants of when inhibition and self-regulation are engaged (Quay, 1988a). When such initiating events arise, self-regulation can result in a reduction in immediately available rewards (self-imposed deprivation) or an increase in the aversive consequences in the immediate context (self-imposed pain or hardship). Yet these self-directed acts may result in later, considerably larger, rewards or the avoidance of later, and greater, aversive consequences. The net gain of considering both the immediate and delayed consequences would be greater than that achieved by consideration of the immediate consequences alone (Kanfer & Karoly, 1972; Thoresen & Mahoney, 1974).

Circumstances or tasks that involve temporal delays, conflicts in temporally related consequences, or the generation of novel responses most heavily tax the type of behavioral inhibition and self-regulation described here. Tasks requiring resistance to temptation or deferred gratification are of this sort. Among the several dimensions of impulsivity discovered in past research (behavioral and cognitive-motor, typically; Milich & Kramer, 1985; Olson, 1989), it is that dimension reflected in deferred gratification and resistance to temptation, or what others have also called "behavioral inhibition" (White et al., 1994), that

is associated with the inhibitory processes described here. Problem-solving tasks are also likely to tax behavioral inhibition and its related executive functions. By definition, *problems* are situations for which the individual has no readily available response and that require the generation of a novel response to resolve. And so problem-solving tasks, tasks involving temporal delays, and tasks involving temporal conflicts in outcomes would all prove useful in research studying not only the linkages between behavioral inhibition and the four executive functions in development but their impairment in ADHD as well.

It is the behavioral dimension of impulse control, rather than the cognitive dimension of impulsiveness (as measured by the Matching Familiar Figures Test and the Draw-A-Line Slowly Test), that seems to be most stable over development, to correspond most closely to parent or teacher ratings of hyperactive-impulsive behavior, and to correlate most highly with later cognitive and social competence (Mischel, Shoda, & Peake, 1988; Olson, 1989; Silverman & Ragusa, 1992). This may explain why methods of assessing the behavioral type of inhibition (parent-teacher ratings, delayed reward tasks, and reinforcer conflict tasks) have been more useful than those assessing cognitive impulse control in distinguishing those with ADHD from those without it, in predicting which infants and preschool children are at risk for ultimately developing ADHD, and in predicting the extent of later cognitive and social problems associated with ADHD, as shown below.

The immediate purpose of the four executive functions described below seems to be the achievement of greater prediction and control over the individual's own behavior and environment, but their ultimate purpose seems to be an alteration in the future consequences a response is likely to produce (Bronowski, 1977; Fuster, 1989; Skinner, 1953). Such executive functions likely arise from (a) the development of neural networks within the prefrontal lobes, which underly these neuropsychological abilities and permit the acquisition of more specific skills used for self-control (Bronowski, 1977; Fuster, 1989); (b) the success these actions have had in the past for maximizing the net consequences of behavior, both immediate and delayed, when considered across long time periods (Kanfer & Karoly, 1972); (c) the socialization of the child; and (d) the ongoing reinforcement of the individual for using self-regulatory actions (Hayes, 1989; Kopp, 1982; Skinner, 1953). The teleological trap set here by the use of terms that connote future, purpose, or intent can be dealt with by recognizing that such apparently future-directed behaviors are actually determined by experience and by ongoing self-directed actions such as self-directed speech and self-directed imaging (Fuster, 1989).

### Origins of the Model

Much of the present model linking inhibition to four executive functions was set forth by Bronowski (1967) 30 years ago. Bronowski's theory has been discussed in more detail elsewhere as it pertains to ADHD (Barkley, 1994). The present explication differs substantially from the initial application of Bronowski's ideas to ADHD (Barkley, 1994, 1995) in the following respects:

(a) the incorporation of portions of Fuster's (1989, 1995) theory and the views of others (Knights, Grabowecky, & Scabini, 1995; Milner, 1995) on the neuropsychological functions subserved by the prefrontal cortex into a new hybrid model; (b) the inclusion of more precise definitions of behavioral inhibition and self-regulation; (c) the addition of a motor control-fluency-syntax component to the model; (d) the inclusion of the self-regulation of drive and motivation as well as that of emotion in the model; (e) the reconfiguration of the model components more logically than before (Barkley, 1994); (f) the addition of numerous recent findings bearing on the linkages among these components and their applicability to ADHD; and (g) additional predictions about ADHD.

In some sense, the evidence reviewed in this article in support of the hypothesized link between inhibition and executive functions, and even the extension of Bronowski's (1967, 1977) theory to ADHD, would have been anticipated by his theory and could be viewed as subsequent validation of it. The model developed here also includes the later theory of Fuster (1989, 1995) on the neuropsychological functions of the prefrontal cortex, which was drawn from his extensive review of the animal and human neuropsychological literatures pertaining to these functions. Though developed independently, and for somewhat different purposes, Bronowski's and Fuster's models have a substantial number of similarities, so their combination into a hybrid model of behavioral inhibition and executive functions makes sense. Space permits only a brief summary of these two earlier theories to illustrate their many points of overlap.

### *Bronowski's Theory on the Uniqueness of Human Language*

Bronowski (1977) identified four unique properties of human language that distinguish it from the languages of animals. He argued that human language is distinctive because it is not simply a means of communication but of reflection, during which plans of action are proposed, played out, and tested. Reflection can only happen if there is a delay between the arrival of a stimulus or event and the response to that event. Bronowski treated this capacity to inhibit and delay responses as the central and formative feature in the evolution of the unique features of human language. It is not just the response that is being delayed but the decision to respond (Bronowski, 1976). Four consequences flow from the evolution of this ability to inhibit and delay responses: prolongation, separation of affect, internalization, and reconstitution. The capacity to delay responses as well as the four consequent mental functions flowing from it are attributed to the brain's prefrontal cortex.

*Prolongation* is the ability to refer backward and forward in time and to exchange messages with others that propose action in the future. This prolongation of reference, or the relation of past events to future actions, requires a special form of memory. During the delay in responding, the features of the signal, situation, or event must be briefly prolonged, fixed, and held in some symbolic form, so they can be retained for later recall when they will serve to revive the responses associated with them in the future. The recall of the past and the manipulation of the imagery of recall permit the construction of hypothetical situa-



tions and their associated consequences. From such conjecturing, plans can be formulated and anticipatory behaviors initiated. This form of memory is, in a sense, remembering so as to do. It is similar to the contemporary concept of working memory in neuropsychology (for reviews, see Becker, 1994). For instance, Goldman-Rakic (1995) defined working memory as "the ability to keep an item of information in mind in the absence of an external cue and utilize that information to direct an impending response" (p. 57). This form of memory and the prolongation of reference it affords are said to permit both imagination and the concept of time. The recall of the past surely is of the self-past, and the holding in mind of present events is the self-present, both of which should contribute to self-awareness. Thus are the functions of working memory, hindsight, forethought, anticipatory set, sense of time, and self-awareness dependent on inhibition.

A second, subsidiary consequence of inhibition and response delay is the *separation of affect*. This refers to the separation of the emotional charge from the content of a message or event and, as a result, the separation of the emotional valence from the content of the response to the event. This involves the self-regulation of emotion apart from motor behavior, and it affords the generation of neutral responses despite emotionally provocative events that may elicit highly charged feelings within the individual. Examples include remaining silent or speaking calmly when angered.

The delay between event and response also permits time for the event to be referred to more than one center in the brain and gives rise to an inner discussion of alternatives before a response is formed. This *internalization of language* gives a unique form to human thought and speech. During the delay in responding, language comes to be turned on the self. It thereby moves from being primarily a means for communication with others to one of communication with the self, a means of reflection and exploration that permits the construction of hypothetical messages or responses before one is chosen to utter or perform. It also permits the creation of self-directed instructions and thereby becomes a fundamental tool for self-control. In supporting his assertions, Bronowski (1967, 1977) referenced the views of Vygotsky (1978, 1987), so they are briefly discussed here.

Vygotsky's (1978, 1987) theory on the development of private speech remains the most accepted view on the topic at this time (Berk, 1994). Such speech starts out as "speech uttered aloud by children that is addressed either to the self or to no one in particular" (Berk & Potts, 1991, p. 358). In its earliest stages, it is thought spoken out loud that accompanies ongoing action. As it matures, it functions as a form of self-guidance and direction by assisting with the formulation of a plan that will eventually assist the child in controlling his or her own actions (Berk & Potts, 1991). Gradually, speech becomes progressively more private or internalized, and behavior comes increasingly under its control; private speech thus becomes internal verbal thought that can exert a substantial controlling influence over behavior. This internalization of speech proceeds in an orderly fashion. It seems to evolve from more conversational, task-irrelevant, and possibly self-stimulating forms of speech to more descriptive, task-relevant forms and then on to more prescriptive and self-guiding speech. It then progresses to more

private, inaudible speech and finally to fully private, subvocal speech (Berk, 1986, 1994; Berk & Garvin, 1984; Berk & Potts, 1991; Bivens & Berk, 1990; Frauenglas & Diaz, 1985; Kohlberg, Yaeger, & Hjertholm, 1968).

The internalization of language brings with it the fourth consequence of inhibition, which Bronowski (1977) called *reconstitution*. It comprises two processes. The first is *analysis*, which is the decomposition of sequences of events or messages into their parts. This allows the progressive redistribution of the event or message to other parallel information-processing systems within the brain

so that its cognitive content becomes more particularized, and its hortative content more generalized . . . The physical world is pictured as made up of units that can be matched in language, and human language itself thereby shifts its vocabulary from command to description or predication. (Bronowski, 1977, p. 121)

The second process is *synthesis*, wherein these parts can be manipulated and used to construct or reconstitute entirely new messages or responses to others. In addition, because the units in such messages can represent and initiate units of behavior, those behavioral units also can be reconstituted into entirely novel behavioral structures. This gives a synthetic and increasingly hierarchical structure to both human language and behavior. Increasingly complex, novel units come to be formed out of more elemental ones, and thus a layered structure to behavior is created. Reconstitution, it is argued, creates the potential for original productivity in human language and hence in the human actions controlled by that language (Bronowski, 1977). The rules or syntax for the sequencing of these verbal and behavioral productions are an inherent part of the process of reconstitution.

Reconstitution is quite evident in verbal fluency and discourse because they represent the capacity to rapidly access and reconstitute parts of speech into complete messages for others. The speed, accuracy, fluency, syntax, and general efficiency with which cognitive content is translated into units of speech and then into whole messages to others reflect the synthetic function of reconstitution. Verbal reconstitution should be most evident in confrontational language tasks or in goal-directed speech or writing, where ideas must be rapidly conveyed to achieve the goal of the task. However, it should also be evident in goal-directed behavioral creativity in general because this reflects the capacity to generate a variety of novel, complex sequences of behavior directed toward goals. Various hypothetical futures and the potential responses to them can now be internally simulated and tested before one is executed.

Bronowski (1977) attributed these four executive functions to the prefrontal lobes. Consequently, theories of and research findings on the functions subserved by this cortex may have some bearing on the many questions left open by Bronowski's theorizing. They may also have something to say about ADHD, given that the origin of ADHD has been repeatedly ascribed to this same brain region (Benton, 1991; Heilman, Voeller, & Nadeau, 1991; Mattes, 1980). Several neuroimaging studies also support this view (Castellanos et al., 1994; Lou, Henriksen, & Bruhn, 1984; Lou, Henriksen, Bruhn, Borner, & Nielsen, 1989; Rapoport, 1996; Sieg, Gaffney, Preston, & Hellings, 1995).

### *Fuster's Theory of Prefrontal Functions*

Fuster's (1989, 1995) theory of prefrontal functions was proposed apparently independently of Bronowski's (1977) model, yet the two have much in common. Fuster concluded that the overarching function of the prefrontal cortex is the formation of cross-temporal structures of behavior that have a unifying purpose or goal. It is the novelty of these behavioral structures, and especially the temporal discontinuities among their elements, that makes the prefrontal cortex essential in their formation. To a lesser extent, their complexity may additionally necessitate the involvement of the prefrontal cortex. However, complexity alone is not sufficient to place such acts within the purview of the prefrontal cortex. On the other hand, time being inserted between the elements of the contingency (i.e., event, responses, and consequences) would be sufficient to do so. Similarly, novelty of the response would also lead to involvement of the prefrontal lobes.

It is this synthesis of novel, cross-temporal behavioral structures mediating cross-temporal contingencies that requires the involvement of prefrontal functions. It is also the goal they subservise that defines these behaviors and gives them cohesion and direction. Smaller sequences of behavior linked over shorter time periods can be used to create longer, more complex units of behavior with increasing durations and complexities and longer term objectives. This pyramiding of simpler units of behavior into more complex ones produces a hierarchical structure to goal-directed behavior and bridges the temporal delays. This function is quite similar to Bronowski's (1977) concept of reconstitution.

Several functions must occur for behavioral structures to be linked across time. Two of these are temporally symmetrical and are called retrospective and prospective functions. The *retrospective function* entails the retention of information about past events that are held in their temporal sequence as they pertain to a goal. Such memory is provisional, having timeliness and term, and permits the referring of current events to previous events in a sequence as well as the retention of action-related information derived from that analysis. The retrospective function gives rise to formulation and retention of a goal-directed behavioral structure. This forms the *prospective function*, and it leads to a preparation to act in anticipation of events or an *anticipatory set*. The behavioral scheme and its relevant events are temporarily represented, deployed in the preparation to act and the execution of those actions, and retained until the goal has been accomplished. These functions are identical to Bronowski's (1977) concepts of prolongation, hindsight, and forethought, as well as to the neuropsychological concept of working memory (Fuster, 1989, 1995).

Fuster (1989, 1995) argued that the proficiency of working memory is dependent on response inhibition and interference control, just as Bronowski (1977) had done. It is in working memory that goals and intentions to act are retained and that action plans are formulated and used to guide the performance of the goal-directed responses. The delay in responding, during which the cross-temporal behavioral structures are being formed and retained, is a critical time that requires protection from a variety of sources of interference that can pervert, distort, or

completely disrupt the planning taking place. Internal sources may also interfere, such as traces of information still held in working memory from the formation of immediately previous behavioral structures. This retention of previous motor plans past their timeliness and term can lead to perseveration of responding. Old habits more familiar to the individual or having similarity to ongoing behavior may likewise disrupt this synthetic, goal-directed function, as might impulses to immediate gratification.

The dissociation of an inhibitory function from a working memory function is not only conceptual but neuroanatomical as well. The inhibitory functions are ascribed to the orbital-frontal regions of the prefrontal cortex and its reciprocal interconnections with the ventromedial region of the striatum (Iversen & Dunnett, 1990). The functions of working memory are subserved by the dorsolateral region of the prefrontal cortex and its reciprocal connections to the more central region of the striatum (Iversen & Dunnett, 1990). Substantial evidence from neuropsychological and neuroimaging studies supports this dissociation (D'Esposito et al., 1995; Fuster, 1989, 1995; Goldman-Rakic, 1995; Iversen & Dunnett, 1990; Knights et al., 1995; Milner, 1995; Vendrell et al., 1995; Williams & Goldman-Rakic, 1995). Even within working memory, the retrospective (sensory) and prospective (motor setting) elements are likewise dissociable though interactive functions (Fuster, 1995; Goldman-Rakic, 1995). Each may be subserved by separate, neighboring, and interacting cortical regions in the dorsolateral prefrontal lobes.

This capacity for holding events in mind in a correct temporal sequence may give rise to the psychological sense of time (Michon, 1985). If so, time perception would be directly dependent on the integrity of working memory, as Bronowski (1977) claimed. A subjective sense of time would seem to be critical in Fuster's (1989, 1995) model as well, given his emphasis on the cross-temporal organization of behavior as being the major function of the prefrontal cortex. A capacity for marking time and sensing its passage would be essential to anticipatory setting of motor responses in preparation for the arrival of impending events. That sense would also be necessary for programming the syntax or temporal structure of the complex behavioral chains generated in the service of goal attainment.

The initiation and maintenance of cross-temporal, goal-directed actions require that the prefrontal cortex assist in regulating basic drive or motivational states in the service of such goal-directed acts. Otherwise, new behaviors would rarely be initiated or sustained on the way to their intended goal. Hence the self-regulation of drive and motivational states in the service of goal-directed actions appears to be another function of the prefrontal cortex. Fuster (1989, 1995) also recognized that disorders of the prefrontal cortex often give rise to disturbances in the regulation of affective and emotional states. Yet he found these difficult to interpret within his model. Bronowski (1977), in contrast, made the separation and self-regulation of affect one of the major consequences of delayed responding in his model. As discussed later, drive and motivation appear to be part of the same functional brain system that governs emotion (Lang, 1995), so the capacity to self-regulate affect may also entail the capacity to self-regulate motivation.

These functions of the prefrontal cortex clearly influence motor control. The prefrontal cortex is unnecessary for the performance of any motor act or even complex, overlearned responses. It is essential for the orderly execution of novel, complex behaviors having a cross-temporal structure. Thus, working memory, hindsight, forethought, sense of time, anticipatory set, and the goal-directed behavioral structures they create influence motor control, fluency, flexibility, syntax, and persistence as they pertain to goal-directed actions. This influence of executive functions over motor control could be seen in three ways, Fuster (1989) concluded (a) in the retention of information about past events and acts already executed that then feeds forward to influence subsequent responding (i.e., a sensitivity to errors), (b) in the anticipatory setting of the premotor and motor functions (i.e., a preparation to act), and (c) in the inhibition of motor impulses inappropriate to the goal or task. A lack of the inhibitory control that provides for the delay of responses and protection of the delay from interference would have many manifestations, Fuster reasoned, including distractibility, hyperreactivity, and impulsivity—the very symptoms attributed to ADHD.

#### A Hybrid Neuropsychological Model of Executive (Self-Regulatory) Functions

To combine the constructs identified in each of these highly overlapping theories into a single model appears to create a more thorough accounting of self-control through these executive functions than does either theory alone. For instance, Bronowski's (1977) theory places great emphasis on the internalization of speech, not only for the control over behavior it provides but also for its value in the creation of novel, complex goal-directed behaviors (reconstitution). Fuster (1989) initially overlooked this important realm of human self-regulation, perhaps because he was attempting to integrate the human and primate literatures to deduce the similarities in the functions of the prefrontal cortex. However, he included verbal behavior within the purview of his model of prefrontal functions (Fuster, 1995), though its role in self-control still seems undervalued. Fuster made explicit mention of the role of the prefrontal cortex in the creation of drive or motivational states that facilitate goal-directed behavior. Bronowski did not concern himself with this function, most likely because his brief essay was intended to focus primarily on the uniqueness of human language. Both noted the critical nature of a special kind of memory (working memory) that gives rise to hindsight, forethought, anticipatory behavior, and goal-directed or purposive action (see also Baddeley & Hitch, 1994). Bronowski additionally linked this special form of memory to the development of the subjective sense of time and the future.

Both theorists also noted the unique capacity of humans to create extraordinarily complex and novel behavioral structures in the service of attaining future goals, and both assigned this analytic-synthetic ability (reconstitution) to the prefrontal cortex. It is this function in combination with that of working memory that gives rise to the capacity for the internal simulation of potential behaviors or, as Bronowski (1977) noted, the conjecturing of hypothetical futures. Both theorists also observed that the syntax (organizational rules) of behavior generally, like

that of speech production specifically, appears to arise out of this special function of the prefrontal cortex, as others also noted (Knights et al., 1995). Thus, the combination of these theories into a hybrid model of executive prefrontal functions deals with the apparent gaps in each.

The hybrid model developed below specifies that behavioral inhibition permits the proficient performance of four executive abilities: working memory, internalization of speech, self-regulation of affect-motivation-arousal, and reconstitution. The four executive functions influence the motor system in the service of goal-directed behavior, labeled *motor control-fluency-syntax* in the model. The motor control-fluency-syntax component emphasizes not only the features of control or management of the motor system which these executive functions afford but also the synthetic capacity for generating a diversity of novel, complex responses and their sequences in a goal-directed manner. Such complex behavior requires a syntax that is placed for now within the reconstitution component of the model that must be translated into actual motor responding. So the generation of behavioral syntax is placed under the reconstitution component, whereas its translation into the actual execution of motor syntax is placed within the motor control component.

These functions originate within the brain's motor system, broadly construed (prefrontal and frontal cortex). However, they may also produce effects beyond the motor system, such as on the sensory-perceptual, linguistic, memory, emotional, and other brain systems in an executive, managerial manner to the extent that the regulation of those other brain systems is necessary for the execution of goal-directed behavior. Thus, although the memory, linguistic, spatial, emotional, or even perceptual systems are viewed as brain systems relatively independent of the prefrontal cortex, these nonexecutive systems may be influenced by the executive system as needed in the service of goal-directed behavior.

The model is shown in Figure 1, along with the subfunctions believed to take place within each component. I have already described most of these subfunctions, but a few have been added or modified slightly, particularly in the domains of the self-regulation of affect and in the internalization of speech, and so require brief clarification here.

#### *Behavioral Inhibition*

As previously defined, behavioral inhibition in Figure 1 refers to three inhibitory functions. These exert a direct controlling influence over the motor system, hence the direct downward arrow in Figure 1 between behavioral inhibition and motor control-fluency-syntax. Behavioral inhibition, however, does not directly cause the four intermediate executive functions to occur but merely sets the occasion for their performance. Visibly representing this crucial point, the lines connecting inhibition to those four executive functions are blunted. But because those executive functions produce direct and causal effects on motor control, arrows connect each executive function with motor control.

#### *Self-Regulation of Affect-Motivation-Arousal*

This component includes Bronowski's (1977) concept of the separation and self-regulation of affect. Unlike Bronowski, how-

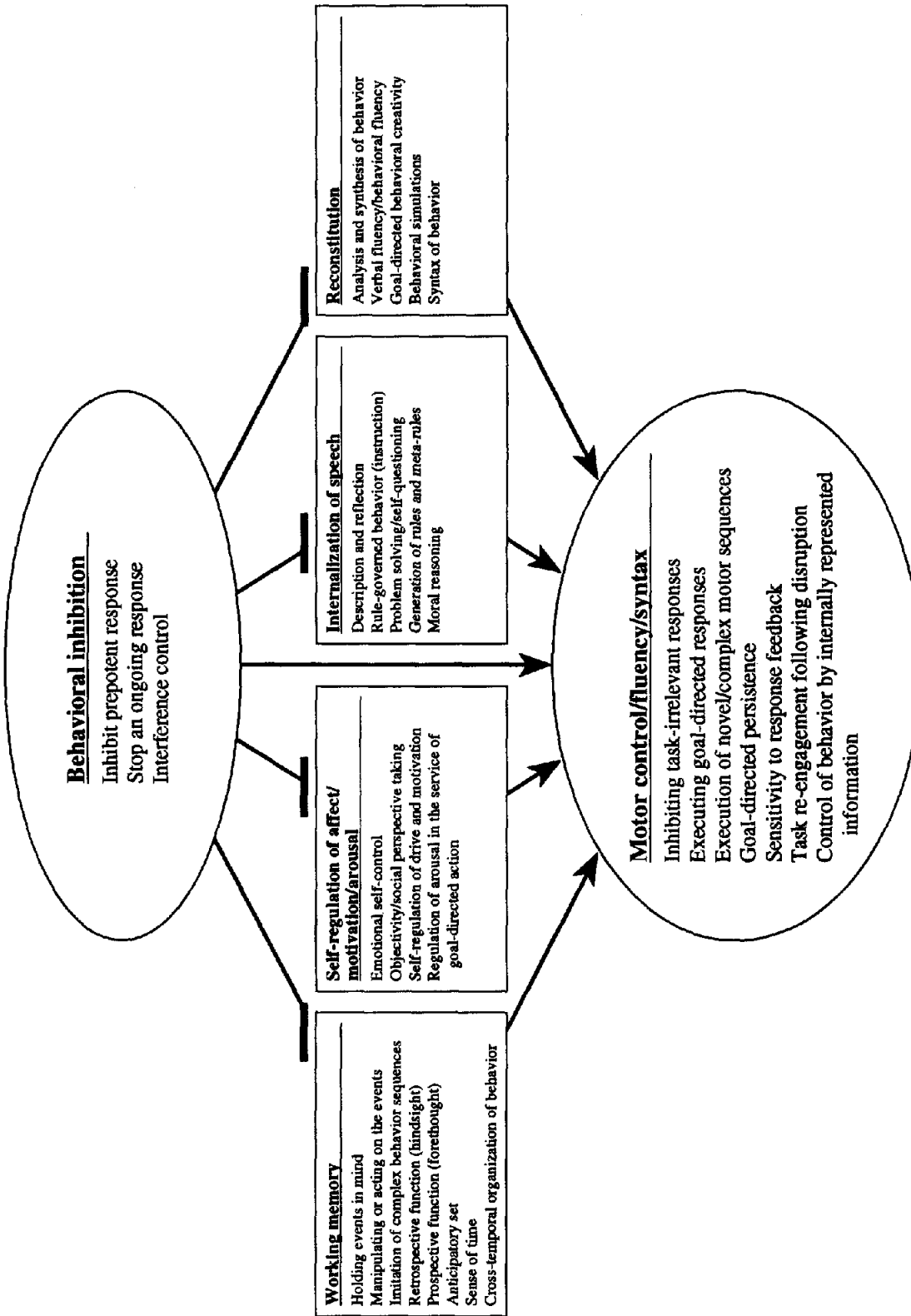


Figure 1. A schematic configuration of a conceptual model that links behavioral inhibition with the performance of the four executive functions that bring motor control, fluency, and syntax under the control of internally represented information.

ever, I believe that affect may not be completely separable from the decision to respond or even from the response itself (see Dimasio, 1994). Instead, a more self-regulatory role of the executive system is stressed here in that emotions, once elicited, come to be moderated or regulated by self-directed, executive actions. Included in this component is also the self-generation of drive or motivational and arousal states that support the execution of goal-directed actions and persistence toward the goal. This combination into a single component makes some sense. Lang (1995) cogently argued that the array of human emotions can be reduced to a two-dimensional model, of which one dimension is motivation (reinforcement and punishment) and the other, level of arousal. So the ability to self-regulate and even induce emotional states as needed in the service of goal-directed behavior also may involve the ability to regulate and induce motivation, drive, and arousal states in support of such behavior. Thus, children may learn to create more positive emotional and motivational states in themselves when angered, frustrated, disappointed, saddened, anxious, or bored by learning to manipulate the variables of which such negative states and their positive alternatives are a function (Cole, Zahn-Waxler, & Smith, 1994; Eisenberg et al., 1993; Kopp, 1989). Such self-directed actions may involve efforts at self-comforting, self-directed speech, visual imagery, and self-reinforcement, among other means (Kopp, 1989). This process of self-regulating affect may begin as early as 5–10 months of age (Stifter & Braungart, 1995). It is also conceivable that children may learn to self-regulate arousal levels for the purposes of goal accomplishment. This component of the model, therefore, includes the following subfunctions, all of which are performed in the service of goal-directed actions: (a) the self-regulation of emotion, (b) a capacity for objectivity and social perspective, (c) the self-regulation of drive and motivational states, and (d) the self-regulation of arousal.

Among the variety of human emotions, it may be the negative ones that are most in need of such self-control (Kopp, 1989). This is because negative affect may prove more socially unacceptable and thereby produce more salient, long-term negative social consequences for the individual relative to the positive emotions, such as laughter or affection. In the immediate context, such negative displays may achieve positive reinforcement or, more likely, escape from or avoidance of aversive events (Patterson, 1982, 1986).

### *Internalization of Speech*

Fuster's (1989) model had little to say about the internalization of speech as a function of the prefrontal cortex. Bronowski (1977), however, stressed the uniqueness and importance of the self-direction and internalization of speech and the profound control it may exert on the individual's behavior. Developmental psychologists (Berk & Potts, 1991; Kopp, 1982) and developmental neuropsychologists (Vygotsky, 1978, 1987) have likewise emphasized the importance of this process for the development of self-control. So I have included it here. Berk and Potts argued that the influence of private speech on self-control certainly may be reciprocal—inhibitory control contributes to the internalization of speech, which contributes to even greater self-restraint and self-guidance. Despite this reciprocity, initial pri-

macy within this bidirectional process is given here to behavioral (motor) inhibition. Self-directed speech also is believed to provide a means for reflection, description, and self-questioning through language, creating an important source of problem-solving ability as well as a means of formulating rules and plans. Eventually, rules about rules (metarules) can be generated into a hierarchically arranged system that resembles the concept of metacognition in developmental psychology (Flavell, Miller, & Miller, 1993). The combination of internal speech with the prospective function of working memory (forethought) may well contribute to moral reasoning (the internalization of community norms, mores, or morals). And so I have listed these various functions related to internal speech under this component of Figure 1.

Although the progressive shift from public to private speech is fascinating in its own right, a more important aspect of this privatization may be the increasing control language comes to have over motor behavior with development (Berk & Potts, 1991; Vygotsky, 1978). This control has been referred to within behavioral analysis as *rule-governed behavior* (Cerutti, 1989; Hayes, 1989; Skinner, 1953). *Rules* are defined as behavior-specifying stimuli. Language constitutes a large class of such stimuli. Skinner hypothesized that this influence of language over behavior occurs in three stages: (a) the control of behavior by the language of others; (b) the progressive control of behavior by self-directed and eventually private speech, as discussed above; and (c) the creation of new rules by the individual, which came about through the use of self-directed questions (second order rules). Both Bronowski (1977) and Skinner stressed two important aspects of internalized speech. One was informational—the power of self-directed speech for description, reflection, and the creation of new rules by which to guide behavior (problem solving). The other was instructive—the power of these messages to actually control motor responses. Rule-governed behavior appears to provide a means of sustaining behavior across large gaps in time among the units of a behavioral contingency (event–response–consequence). By formulating rules, the individual can construct novel, complex (hierarchically organized), and prolonged behavioral chains. These rules can then provide the template for reading off the appropriate sequences of behavioral chains and can guide behavior toward the attainment of a future goal (Cerutti, 1989). By this process, the individual's behavior is no longer under the total control of the immediate surrounding context. Control of behavior is now shifted to internally represented information (rules). The control of behavior by the sense of past and future, as well as by the more general rules or metarules formulated from them or acquired through socialization, most likely makes some contribution to the development of conscience and moral reasoning (Hoffman, 1970; Kochanska, DeVet, Goldman, Murray, & Putnam, 1994).

Hayes (1989) and Cerutti (1989) stipulated a number of specific effects on behavior that rule governance produces. These become important later as predictions from the model about ADHD: (a) The variability of responses to a task is much less when rule-governed behavior is in effect than when behavior is contingency shaped (developed and maintained by the environmental contingencies alone); (b) behavior that is rule

governed may be less affected or entirely unaffected by the immediate contingencies operating in a situation or by momentary and potentially spurious changes in those contingencies; (c) when rules and immediate contingencies compete in a given situation, the rule is more likely to gain control over the individual's behavior, and this will be progressively more the case as the individual matures; (d) rule-governed responding under some conditions may be rigid or inflexible, even if the rule being followed is incorrect; and (e) self-directed rules permit individuals to persist in responding under conditions of very low levels of immediate reinforcement, or even in the absence of reward, as well as during extreme delays in the consequences for responding.

In short, self-directed rules assist with bridging temporal gaps in behavioral contingencies and thus contribute to the cross-temporal organization of behavior. The motor execution of such verbal rules appears to be partially dependent on the capacity to retain them in working memory and to inhibit prepotent or irrelevant responses that compete with the rule (Zelazo, Reznick, & Pinon, 1995).

### *Motor Control–Fluency–Syntax*

The self-directed and frequently private actions constituting these four executive components serve to create a shift in the control of behavior, from control exclusively by the external environment to control by internally represented information (Fuster, 1989, 1995; Godbout & Doyon, 1995; Goldberg & Podell, 1995; Goldman-Rakic, 1995). Both sensory input as well as motor behavior that is unrelated to the goal and its internally represented behavioral structures become minimized or even suppressed. This occurs not only during the performance of these four executive functions but also during the execution of the complex, goal-directed motor responses they generate. Throughout the execution of goal-directed behaviors, working memory permits the feedback from the last response(s) to be held in mind (retrospective function) and fed forward (prospective function) to modify subsequent responding; thus a sensitivity to errors is created. Just as important, when interruptions in this chain of goal-directed behaviors occur, the individual is able to disengage, respond to the interruption, and then re-engage the original goal-directed sequence because that plan has been held in mind despite the interruption. Thus, inhibition sets the occasion for the engagement of the four executive functions, which then provide considerably greater control of behavior by the internally represented information they generate.

### Extension of the Model to ADHD

Tremendous progress has been made in the last 2 decades in understanding the neuropsychological functions subserved by the prefrontal cortex. This progress has led to the development of theories for organizing and explaining these functions (Fuster, 1989, 1995). Increasing evidence suggests that ADHD appears to arise from abnormalities in the structure and function of the prefrontal cortex and its networks with other brain regions, especially the striatum (Castellanos et al., 1994; Heilman et al., 1991; Lou et al., 1984, 1989; Rapoport, 1996; Seig et al., 1995;

Zametkin et al., 1990). A model of prefrontal executive functions, therefore, should offer some promise as a model for understanding ADHD as well.

The hybrid model developed in Figure 1 predicts that the deficiency in behavioral inhibition that characterizes ADHD diminishes the effective deployment of the four executive abilities that subservise self-control and goal-directed behavior. This inhibitory deficit thereby indirectly disrupts the control of goal-directed motor behavior by its influence on these executive functions. As a consequence, the behavior of those with ADHD is controlled more by the immediate context and its consequences than is the behavior of others. The behavior of others, in contrast, is more controlled by internally represented information, such as hindsight, forethought, time, plans, rules, and self-motivating stimuli that ultimately provide for the maximization of future net outcomes.

What follows is a brief review of the evidence that supports the view of ADHD as a deficit in behavioral inhibition. This is followed by a selective review of evidence linking behavioral inhibition to each of the components of the present model. Fuster (1989, 1995) and others (Goldberg & Podell, 1995; Goldman-Rakic, 1995; Knights et al., 1995; Milner, 1995; Stuss & Benson, 1986) have reviewed a far more extensive body of evidence from both animal and human neuropsychological research that also supports the existence of these prefrontal functions and their link to inhibitory processes. More important to the purpose here, findings are reviewed that implicate the impairment of these functions among those with ADHD.

### *ADHD and Deficient Inhibition*

The evidence supporting a deficiency in behavioral inhibition in ADHD comes from a number of sources. Many studies using parent and teacher ratings of hyperactive and impulsive behaviors in children find these behaviors to cluster into a single dimension, often called impulsive–hyperactive or undercontrolled behavior (Achenbach & Edelbrock, 1983, 1985; Goyette, Conners, & Ulrich, 1978; Hinshaw, 1987; Lahey et al., 1988, 1994). It is this dimension of behavior that, virtually by definition, distinguishes those with ADHD from others without it (Hinshaw, 1987, 1994). This argument, however, is circular; ratings of hyperactive–impulsive behavior are used to create a diagnostic category of ADHD, and then those with ADHD are found to differ on such ratings. The circularity is dealt with by evidence of external validation from sources other than parent–teacher ratings. Many studies that have used objective measures have shown that children rated as being more hyperactive–impulsive or who were clinically diagnosed as ADHD, in fact, displayed a higher activity level than other children not so rated or diagnosed (Gomez & Sanson, 1994; Porrino et al., 1983; see Luk, 1985, for a review). ADHD children also talk more than other children, whether to others (Barkley, Cunningham, & Karlsson, 1983; Cunningham & Siegel, 1987) or out loud to themselves (Berk & Potts, 1991; Copeland, 1979), and make more vocal noises than do other children (Copeland & Weissbrod, 1978). All of this may be taken as evidence of poor behavioral inhibition.

Children with ADHD, compared with controls, also have

more difficulties restricting their behavior in conformance with instructions to do so (Barkley & Ullman, 1975; Milich, Landau, Kilby, & Whitten, 1982; Routh & Schroeder, 1976; Ullman, Barkley, & Brown, 1978), deferring gratification (Campbell, Pierce, March, Ewing, & Szumowski, 1994; Rapport, Tucker, DuPaul, Merlo, & Stoner, 1986), and resisting temptation (Campbell et al., 1994; Campbell, Szumowski, Ewing, Gluck, & Breaux, 1982; Hinshaw, Heller, & McHale, 1992; Hinshaw, Simmel, & Heller, 1995). Again, a significant deficit in inhibition, especially in situations where rewards are immediately available for emitting impulsive responses, might be inferred from these results.

Further evidence of poor inhibition in ADHD comes from studies that used motor inhibition tasks, such as go-no-go paradigms (Iaboni, Douglas, & Baker, 1995; Milich et al., 1994; Shue & Douglas, 1989; Trommer, Hoepfner, Lorber, & Armstrong, 1988; Voeller & Heilman, 1988), the stop-signal task (Oosterlaan & Sergeant, 1995; Schachar & Logan, 1990; Schachar et al., 1993), the change paradigm (related to the stop-signal paradigm; Schachar et al., 1995), and delayed response tasks (Gordon, 1979; Schweitzer & Sulzer-Azaroff, 1995; Sonuga-Barke, Taylor, & Hepinstall, 1992; Sonuga-Barke, Taylor, Sembi, & Smith, 1992). Blurting out incorrect verbal responses and disrupting the conversations of others with such intrusive responses are considered primary symptoms of impulsiveness in those with ADHD (APA, 1994) and have been objectively documented (Malone & Swanson, 1993).

Numerous studies also demonstrate that children with hyperactivity or ADHD produce greater errors of commission on continuous performance tasks, whether computerized (Barkley, 1991; Barkley, DuPaul, et al., 1990; Barkley et al., 1992; Grodzinsky & Diamond, 1992; Robins, 1992; see Corkum & Siegel, 1993, for a review) or given by paper and pencil such as letter cancellation tasks (Aman & Turbott, 1986; Brown & Wynne, 1982; Carte, Nigg, & Hinshaw, in press; Keogh & Margolis, 1976). However, results for the latter tasks, particularly when self-paced, have proven contradictory (Gomez & Sanson, 1994; van der Meere, Wekking, & Sergeant, 1991). Problems with response inhibition in children with ADHD have even been noted on tasks that assess more molecular motor movements, such as ocular gaze shifts on delayed response tasks (Ross, Hommer, Breiger, Varley, & Radant, 1994).

Poor behavioral inhibition likewise should be evident in deficient performances in learning under passive versus active avoidance paradigms. Here passivity or the inhibiting of a response is required to terminate, escape, or avoid punishment. In such tasks, those with ADHD have been found to show more such punished trials than is normal (Freeman & Kinsbourne, 1990; Milich et al., 1994). Poor behavioral inhibition also should be evident when a task requires stopping an ongoing response when signalled to do so or when feedback suggests that the response is ineffective or maladaptive. Many studies of those with ADHD have noted them to have such difficulties (Oosterlaan & Sergeant, 1995; Schachar & Logan, 1990; Schachar et al., 1993, 1995).

The stopping of an ongoing response pattern is required in the performance of the Wisconsin Card Sorting Test (WCST). Patients with frontal lobe damage often have difficulties on this

test, and its performance has been associated with activation of the dorsolateral prefrontal cortex (Berman et al., 1995). Children with ADHD seem to have difficulties performing the WCST as well. Barkley et al. (1992) reviewed 13 studies that used the WCST, 8 of which found significant differences between ADHD and control participants. Methodological problems, such as low statistical power due to small samples and diverse age groups, may well have limited some of the studies that yielded nonsignificant findings. Performance on this test has been shown to improve with age in both children with ADHD and controls (Seidman et al., 1996). Family history of ADHD may also determine the severity of results (Seidman et al., 1996). Even so, of 6 additional studies of ADHD that used the WCST, 4 (Krener, Carter, Chaderjian, Wolfe, & Northcutt, 1993; McBurnett et al., 1993; Seidman et al., 1995, 1996) also found differences between ADHD and control groups on this test; the remaining 2 did not (Narhi & Ahonen, 1995; Pennington et al., 1993). Although the evidence is not entirely consistent, the weight of the evidence shows those with ADHD to have a problem with response perseveration, despite feedback about errors.

In keeping with this interpretation, Sergeant and van der Meere (1988) found that children with ADHD performing an information-processing task were less likely to alter their subsequent responding when they made an error than were children in the control group. Response perseveration in those with ADHD also has been demonstrated in research with the card-playing task (Milich et al., 1994). Similarly, patients with prefrontal lobe injuries have been noted to show persistence in a previously reinforced response pattern, even though the contingencies changed and they could verbally report that such changes occurred (Dimasio, 1994; Rolls, Hornak, Wade, & McGrath, 1994).

According to Fuster (1989), the failure to adjust motor performance given feedback concerning its ineffectiveness may actually reflect an interaction between behavioral inhibition and the retrospective-prospective functions of working memory. The individual fails to hold in mind information on the success of his or her responding on the immediately preceding trials (retrospection), which then feeds forward to influence or even stop immediately future responses (prospection leading to inhibition). If correct, this suggests that the cessation, shifting, and re-engagement of ongoing responses according to task feedback belongs under the motor control component of the model as an effect of working memory on this component. Regardless, this separation of motor shifting and re-engagement from behavioral inhibition has recently been demonstrated in children with ADHD, who were inferior to controls in both processes (Schachar et al., 1995). A distinction between the two processes also suggests that the perseverative responding seen on the WCST by those with ADHD may be less reflective of poor inhibition and more reflective of deficient working memory—an interpretation more consistent with neuroimaging research involving this test (Berman et al., 1995).

#### *Evidence of Poor Interference Control*

Evidence for poor interference control in those with ADHD comes from several sources. Studies that used the Stroop Color-

Word Interference Test with children having ADHD nearly always found them to perform poorly on this test. In a previous review (Barkley et al., 1992), six such studies were located, five of which found children with ADHD to take more time and make more errors than control children during the interference portion of the task. Four more studies produced similar results (Krener et al., 1993; Leung & Connolly, 1996; Pennington et al., 1993; Seidman et al., 1996). The consistency of such findings across studies is striking despite differences in cultures, group selection procedures, and sample sizes. It suggests that a deficiency in the control of interference from prepotent responses is reliably associated with ADHD. Group differences could not be attributed to comorbid learning or conduct disorders (Leung & Connolly, 1996; Pennington et al., 1993; Seidman et al., 1996), which argues for the specificity of these differences to ADHD. Neuroimaging research with this task has identified the orbital–prefrontal regions, particularly the right prefrontal region, as being involved in its performance (Bench et al., 1993; Vendrell et al., 1995). Other neuroimaging studies have found these regions to be significantly smaller than normal in children with ADHD (Castellanos et al., 1994; Rapoport, 1996).

The capacity to maintain performance toward a task despite distraction might also serve as an indicator of poor interference control. Whether or not distractors disrupted task performance, however, would depend on the prepotency of the response likely to be elicited by the distracting event as well as the extent to which any executive functions taking place during the task performance required protection from such interference. Those task-related factors calling for such executive control might be temporal delays, temporally related conflicts in consequences, and problem-solving tasks requiring the formulation of novel, complex responses. Research on ADHD suggests that distractions outside of the immediate task materials are unlikely to differentially affect the performances of children with and without ADHD; distractions embedded within the task seem more likely to do so (Leung & Connolly, 1996). The more salient the type of distraction, the more it occurs within the task; or the more that time and delays occur within the task parameters, the greater the likelihood that distractors will interfere with the task performance by ADHD children (Barkley, Koplowitz, & Anderson, 1996; Bremer & Stern, 1976; Cohen, Weiss, & Minde, 1972; Landau, Lorch, & Milich, 1992; Rosenthal & Allen, 1980; Steinkamp, 1980). Other evidence of poor interference control in ADHD might have been found in a study of college students with ADHD who had more task-irrelevant thoughts during performance of a continuous performance test than did the control group (Shaw & Giambra, 1993). Although this might imply poor interference control over internal sources of distraction, other interpretations could account for these findings.

The studies reviewed above indicate that children with ADHD have difficulties with behavioral inhibition on various tasks (see also Pennington & Ozonoff, 1996). Is there evidence for the inverse relationship as well? That is, do young children with poor behavioral inhibition have a higher likelihood of having symptoms of ADHD? Some studies suggest that this may be the case. Young children identified as more impulsive and less

able to delay responses, particularly in resistance-to-temptation tasks, have been rated by others as displaying higher levels of ADHD symptoms both concurrently and later in development (Campbell & Ewing, 1990; Mischel, Shoda, & Peake, 1988; Mischel, Shoda, & Rodriguez, 1989; Shoda, Mischel, & Peake, 1990; Silverman & Ragusa, 1991). Likewise, children with higher levels of activity at Age 2 displayed less self-control at Age 7 (Halverson & Waldrop, 1976).

To summarize, the evidence that ADHD involves impaired behavioral inhibition seems compelling, arising as it does from multiple studies, methods, and sources. Suggestive evidence from developmental psychology also points to the inverse relationship as well, that early deficits in behavioral inhibition may be predictive of risks for later ADHD symptoms.

### *Working Memory*

The hybrid model in Figure 1 predicts that poor behavioral inhibition, as in ADHD, should lead to secondary deficiencies in working memory and its subfunctions. (a) Children with ADHD should be more influenced by context and less controlled by internally represented information than same-age peers without ADHD. (b) Children with ADHD should be more influenced by immediate events and their consequences than by those more distant in time. (c) Those with ADHD should be less likely to recall and hold in mind information about the past (hindsight) for the formulation of a plan in the future (forethought and planning). (d) Anticipatory or preparatory behaviors founded on such planning should be less evident in those with ADHD, so motor presetting in anticipation of the arrival of future events should likewise be less proficient. (e) A form of temporal myopia should exist in children with ADHD, in that behavior is more controlled by the temporal “now” than by internally represented information pertaining to the past, the future, and the sense of time. (f) Children with ADHD should exhibit less control of behavior by time and more deficient organization of behavior relative to time. (g) Performance under cross-temporal (if–then) contingencies should be less effective in those with ADHD because they cannot bridge the delays in the contingencies, using internally represented information. And (h) the larger the delays in time that separate the components of a behavioral contingency (events, responses, and their consequences), the less successful those with ADHD should be in effectively managing those tasks. There should also be less ability to successfully persist in goal-directed behavior in those with ADHD. And even when those with ADHD undertake goal-directed behavior, it should be subject to greater interference by sources of disruption in both the external and internal environments and result in less success at goal attainment.

The model in Figure 1 predicts six additional deficits in association with ADHD: (a) There should be an inability to imitate lengthy sequences of goal-directed behavior demonstrated by others, given that such sequences cannot be held in mind as well for the orchestration of their execution. (b) The sense of time should be impaired. (c) Information recalled from memory (retrospective function) should be temporally disorganized—that is, the very syntax of recall should be deficient. (d) Consequently, the syntax of motor planning and execution should like-



wise be disorganized. (e) Discourse with others should reflect fewer references to time, the past, and especially the future. And (f) significant deficiencies should exist in the performance of those social skills (i.e., sharing, cooperation, etc.) as well as other adaptive behaviors (i.e., concern for safety, health consciousness, etc.) that are predicated on the valuation of future personal and social consequences over immediate ones. The knowledge of those social and adaptive skills or behaviors is not at issue here; that knowledge should not be deficient in those with ADHD. It is the application of that knowledge in day-to-day functioning that should be impaired. The problem, then, for those with ADHD is not one of knowing what to do but one of doing what you know when it would be most adaptive to do so. This same problem is typical of patients with injuries to the prefrontal cortex (Delis, Squire, Bihle, & Massman, 1992; Stuss & Benson, 1986).

Is there evidence for these predicted deficiencies in impulsive individuals or in those with ADHD? There is limited evidence, mainly because little research has specifically set out to test these predictions. Research on young children suggests that measures of response inhibition (resistance to temptation) appear to be significantly and positively associated with measures of memory for spatial location or working memory (Lee, Vaughan, & Kopp, 1983). The performance of delayed response tasks also requires waiting for a reward while keeping in mind its hidden location. Children as young as 18–30 months of age demonstrate both the presence of such working memory and its apparent dependence on response inhibition (Diamond, Crutten-den, & Neiderman, 1994).

Working memory has often been assessed in neuropsychological research with the following tasks: retention and oral repetition of digit spans (especially in reverse order); mental arithmetic, such as serial addition; locating stimuli within spatial arrays of information that must be held in memory; and holding sequences of information in memory to properly execute a task, as in self-ordered pointing tasks (see Becker, 1994; and Milner, 1995). Consistent with the model, children with ADHD appear to be less proficient in mental arithmetic (Ackerman, Anhalt, & Dykman, 1986; Barkley, DuPaul, et al., 1990; Mariani & Barkley, in press; Zentall & Smith, 1993). Both children and adults with ADHD have also shown more difficulties with repetition of digit spans (particularly backwards; Barkley, Murphy, & Kwasnik, 1996; Mariani & Barkley, in press; Milich & Loney, 1979), memory for spatial location (Mariani & Barkley, in press), and memory for finger-pointing or hand-movement sequences than have control group participants (Barkley, Murphy, & Kwasnik, 1996; Breen, 1989; Grodzinsky & Diamond, 1992; Mariani & Barkley, in press).

The Freedom From Distractibility factor of the Wechsler Intelligence Scale for Children—Revised comprises tests of digit span, mental arithmetic, and coding. These tests entail the use of working memory, among other mental functions. Children with ADHD score more poorly on this factor than do those without ADHD (Anastopoulos, Spisto, & Maher, 1994; Lufi, Cohen, & Parish-Plass, 1990; Milich & Loney, 1979). By themselves, such findings might suggest a variety of problems besides working memory (i.e., deficient arithmetic knowledge, slow motor speed, etc.). However, Zentall and Smith (1993) were able

to rule out these potential confounding factors in their study of mental computation in children with ADHD, thus giving greater weight to deficient working memory in ADHD.

The Tower of Hanoi and Tower of London tasks require that individuals be able to mentally represent and test out various ways of removing and replacing disks on a set of pegs or spindles before undertaking the actual motor execution of the rearrangement. Patients with injuries to the prefrontal cortex often have difficulty performing these tests (Goel & Grafman, 1995; Levin et al., 1994), and neuroimaging research has found activation of the prefrontal cortex to be involved in their performance (Morris, Ahmed, Syed, & Toone, 1993). Studies of ADHD that used these tasks found children with ADHD to perform both tasks more poorly than children without ADHD (Brady & Denckla, 1994; Pennington et al., 1993; Weyandt & Willis, 1994). The tasks have been interpreted (Pennington et al., 1993) as taxing three of the processes represented in the model: working memory, problem solving, and planning. Others, however, believe the Tower of London task at least reflects difficulties in inhibiting prepotent responses (Goel & Grafman, 1995).

The storage and recall of simple information in memory tests has not been found to be impaired in those with ADHD (Barkley, DuPaul, et al., 1990; Cahn & Marcotte, 1995; Douglas, 1983, 1988). Instead, it seems that when more, and more complex, information must be held in mind, especially over a lengthy delay period, deficits become evident (Douglas, 1983, 1988; Seidman et al., 1995, 1996). Also, when strategies are required for organizing material so as to remember it more effectively, those with ADHD perform less well than controls (August, 1987; Benezra & Douglas, 1988; Borcharding et al., 1988; Douglas, 1983; Douglas & Benezra, 1990; Felton, Wood, Brown, Campbell, & Harter, 1987; Frost, Moffitt, & McGee, 1989; Shapiro, Hughes, August, & Bloomquist, 1993).

The use of strategies by children with ADHD to organize complex material has primarily been studied with verbal information. Some studies, however, have used the Rey–Osterrieth Complex Figure Drawing Test. A number of studies of ADHD have identified organizational deficits (Douglas & Benezra, 1990; Grodzinsky & Diamond, 1992; Seidman et al., 1996), but a few others have not (Moffitt & Silva, 1988) or have found deficits only in children with ADHD and reading disorders (McGee, Williams, Moffitt, & Anderson, 1989). The two studies that found nonsignificant results used samples drawn from community screenings of children, whereas those studies that found differences used clinic-referred samples, which perhaps may explain these discrepant results.

As noted earlier, the incapacity to hold information in mind in those with ADHD creates a disability in imitating complex and lengthy behavioral sequences performed by others that may be novel to the individual. I found no studies of ADHD that expressly tested this prediction. However, several studies have found that children with ADHD are less proficient at imitating increasingly lengthy and novel sequences of simple motor gestures than are children without ADHD (Breen, 1989; Grodzinsky & Diamond, 1992; Mariani & Barkley, in press). Adults with ADHD have also been shown to be less able to replicate increasingly longer sequences involving pointing to locations than are adults without ADHD (Barkley et al., in press). Though

hardly definitive, such findings suggest that this prediction is worth testing in future studies of ADHD.

Figure 1 also links poor inhibition with an impaired sense of time (working memory). Gerbing, Ahadi, and Patton (1987) also argued that the performance of time estimation–production tasks may be related to impulsiveness, and White et al. (1994) found some evidence supporting that argument. But more direct evidence for an impairment in the sense of time in children with ADHD has been found in two separate studies by Cappella, Gentile, and Juliano (1977) and in three studies of mine, in which both rating scales assessing the sense of time and its regulation of child behavior and a time reproduction task similar to that used by Zakay (1992) were used (Barkley, Koplowitz, et al., 1996; Koplowitz & Barkley, 1995). In a fourth study, a trend ( $p < .07$ ) was found toward less accurate time estimations by young adults with ADHD despite the limited statistical power of that study. All of these studies had a number of significant methodological flaws, which makes attempts at replication imperative, but their general consistency supports the hypothesis about an impaired sense of time in ADHD.

The model in Figure 1 also predicts that temporal delays should more adversely affect the performance of those with ADHD than that of controls. Numerous studies of ADHD have found that both delays interposed in tasks and temporal uncertainties produce poorer performances (Chee, Logan, Schachar, Lindsay, & Wachsmuth, 1989; Gordon, 1979; Sonuga-Barke, Taylor, & Hepinstall, 1992; Sonuga-Barke, Taylor, Sembi, & Smith, 1992; van der Meere, Shalev, Borger, & Gross-Tsur, 1995; van der Meere, Vreeling, & Sergeant, 1992; Zahn, Krusei, & Rapoport, 1991). Although supportive of a deficit in time, timing, and the cross-temporal organization of behavior in those with ADHD, such delays may simply create boredom and may increase off-task behavior in children with ADHD that proves detrimental to their performance, as suggested in Zentall's (1985) optimal stimulation theory.

Hindsight and forethought have not been well studied in those with ADHD. But if in its most elementary form hindsight can be taken to mean the ability to alter subsequent responses on the basis of immediately past mistakes, then the research findings imply a deficit in hindsight in those with ADHD. Children with ADHD, like adults with prefrontal lobe injuries (Milner, 1995), are less likely to adjust their subsequent responses on the basis of an immediately past incorrect response in an information-processing task (Sergeant & van der Meere, 1988). The findings of perseveration on the WCST, as noted earlier, also suggest such a problem.

Research that used complex reaction time tasks with warning stimuli and preparation intervals may be relevant to the construct of forethought. In such research, children with ADHD often failed to use the warning stimulus to prepare for the upcoming response trial (Douglas, 1983), and longer preparatory intervals were associated with poorer performance in children with ADHD than in control children (Chee et al., 1989; van der Meere et al., 1992; Zahn et al., 1991). The capacity to create and maintain anticipatory set for an impending event also has been shown to be impaired by ADHD (van der Meere et al., 1992).

Maze performance may reflect planning ability or fore-

thought. Some studies have found children with ADHD to perform poorly on maze tasks; others, however, have not (Barkley et al., 1992; Grodzinsky & Diamond, 1992; Mariani & Barkley, in press; McGee et al., 1989; Milich & Kramer, 1985; Moffitt & Silva, 1988). The young age of the participants may be a factor in some of the negative findings (Mariani & Barkley, in press), as may be the low power associated with the use of small samples ( $n < 20$  per group; Barkley et al., 1992; McGee et al., 1989; Moffitt & Silva, 1988). As noted earlier, the Tower of Hanoi and Tower of London tasks may reflect the capacity to plan or "look ahead" (Pennington et al., 1993), and children with ADHD performed poorly on these tasks. Although they are hardly definitive, the findings reviewed here are at least suggestive of deficiencies in hindsight, forethought, and planning ability.

No researchers of ADHD have examined verbal references to time, plans for the future, the future more generally, and other aspects of hindsight and forethought in discourse with others. Also, just how well those with ADHD are able to temporally tag or organize their recall and internal representation of sequential events has not been studied. Such deficits are common in patients with prefrontal lobe injuries (Gershberg & Shimamura, 1995; Godbout & Doyon, 1995), however, which argues for their likely impairment in those with ADHD as well. Recent research on the verbal discourse of children with ADHD (Tannock, 1996) found deficits in the children's organization of sequential material in the retelling of stories, which might imply such a difficulty. Prior studies of narrative ability (Tannock, Purvis, & Schachar, 1992) and elicited language (Zentall, 1988) have also noted organizational deficits in children with ADHD. Although organizational deficits in discourse are suggested by these results, they may also reflect the presence of comorbid language problems known to exist in a substantial minority of children with ADHD (Cantwell, & Baker, 1992). Possibly ruling against such an interpretation is that Tannock (1996) used a control group of children with reading disorders who were known to have language problems, and she still found greater organizational deficits in the ADHD group.

The present model suggests that those with ADHD are less well controlled by internally represented information than are others. Like patients with prefrontal lobe injuries (Stuss & Benson, 1986), those with ADHD may be more controlled by external stimuli. For instance, patients with prefrontal injuries are more likely than nonpatients to have objects in the surrounding context elicit responses that may be appropriate as far as the objects' use is concerned but that are not appropriate in that particular context (e.g., opening an umbrella found inside an examination room; Goldberg & Podell, 1995); such phenomena are referred to as "utilization behavior." The model predicts that utilization behavior should be more evident in children with ADHD, yet no research has been conducted on the issue. Such research might profit from borrowing the methodologies used to study this issue in patients with brain injury (see Goldberg & Podell, 1995).

As noted earlier, those with ADHD have more trouble doing what they know than knowing what to do. Suggestive of this are past studies that have found hyperactive–impulsive children to be more prone to accidents than children who are not so

diagnosed (Bijur, Golding, Haslum, & Kurzon, 1988; Gayton, Bailey, Wagner, & Hardesty, 1986; Methany & Fisher, 1984; Taylor, Sandberg, Thorley, & Giles, 1991), yet hyperactive-impulsive children are not deficient in their knowledge of safety or accident prevention (Mori & Peterson, 1995). Barkley et al. (in press) also found that teens and young adults with ADHD have significantly more motor vehicle accidents and exhibit other driving risks (speeding) but demonstrate no deficiencies in their knowledge of driving, safety, and accident prevention.

### *Self-Regulation of Affect-Motivation-Arousal*

Inhibition is important in the development of emotional self-regulation (Kopp, 1989). Figure 1 makes the following predictions about those who have deficiencies in inhibition, as in ADHD. They should show (a) greater emotional reactivity to emotionally charged immediate events; (b) fewer anticipatory emotional reactions to future emotionally charged events (in view of the decreased capacity for forethought); (c) decreased ability to act with the impact of their emotions on others in mind; (d) less capacity to induce and regulate emotional, drive or motivational, and arousal states in the service of goal-directed behavior (the further away in time the goal, the greater the incapacity to sustain the arousal and drive toward the goal); and, the corollary of d, (e) a greater dependence on external sources affecting drive, motivation, and arousal that are within the immediate context in determining the degree of persistence of effort in goal-directed actions.

Only a few of these predictions have been examined in research. The development of inhibition has been shown to be important for developing self-regulation of emotion and motivation (see Garber & Dodge, 1991; Kopp, 1989; and Mischel et al., 1989, for reviews). Preschool children's emotional responses to disappointment also have been shown to be related to self-regulation and disruptive behavior patterns (Cole et al., 1994). Similarly, children's emotional intensity and negative emotion have also been related to teacher ratings of interference control (Eisenberg et al., 1993). And Shoda et al. (1990) also found significant associations between inhibition in a resistance-to-temptation task in children's preschool years and parent ratings of the same children's emotional control and frustration tolerance at adolescence.

More evidence of a link between inhibition and emotional self-regulation comes from research on neurologically injured patients. Disorders of emotion are common in individuals with injury sustained to the prefrontal cortex, which suggests that this region is critical not only for inhibition but for the self-control of emotion (Fuster, 1989; Rolls et al., 1994; Stuss & Benson, 1986). The emotional changes secondary to frontal lobe injury can be grouped into three types of disturbance: (a) disorders of drive or motivation, (b) subjective emotional experience (mood), and (c) emotional expression (affect; Stuss, Gow, & Hetherington, 1992). Emotional hyperreactivity, irritability, low frustration tolerance, loss of emotional self-control, and lack of concern for others (Rolls et al., 1994) are commonly noted in such patients. Although these findings are suggestive of a link between behavioral inhibition and emotional self-regulation, they do not confirm it.

Irritability, hostility, excitability, and a general emotional hyperresponsiveness toward others have been frequently described in the clinical literature on ADHD (see Barkley, 1990; Still, 1902). Douglas (1983, 1988) anecdotally observed and later objectively documented the tendency of children with ADHD to become overaroused and excitable in response to rewards and to be more visibly frustrated when past rates of reinforcement declined (Douglas & Parry, 1994; Wigal et al., 1993, cited in Douglas & Parry, 1994). Rosenbaum and Baker (1984) also reported finding greater negative affect expressed by children with ADHD during a concept learning task involving noncontingent negative feedback. And Cole et al. (1994) found that levels of negative affect were significantly and positively correlated with symptoms of and risk for ADHD but only in boys. The opposite proved true for girls.

The foregoing studies intimate that emotional self-control may be problematic for children with ADHD. However, children with ADHD may experience a greater number of failures on such tasks because of their other cognitive deficits (working memory) or comorbid learning disabilities that could lead to greater frustration and other negative emotional reactions. Future researchers must therefore take care to equate the levels of success between children with and without ADHD before concluding that children with ADHD are more emotional during their performance on learning tasks.

Greater emotional reactivity has been reported as well in the social interactions of children with ADHD. E. J. Mash (personal communication, February 1993) found that children with ADHD displayed greater emotional intonation in their verbal interactions with their mothers than children without ADHD. Studies of peer interactions have also found children with ADHD, compared with those without ADHD, to be more negative and emotional in their social communications with peers (Pelham & Bender, 1982). The commonly noted association of ADHD with defiant and hostile behavior (for reviews, see Barkley, 1990; and Hinshaw, 1987) may, at least in part, stem from a deficiency in emotional self-regulation in those with ADHD. Again, however, these findings are merely suggestive rather than confirmatory of such a link.

The model also predicts that the perception of others' emotions will not be affected by ADHD because such perception is nonexecutive in nature. The only study of this issue of which I am aware supports this view (Shapiro et al., 1993), but caution must be exercised, given the many possible explanations for a failure to reject the null hypothesis.

As for ADHD being associated with less drive, motivation, or effort in the performance of goal-directed behaviors, researchers have frequently commented on the appearance of such difficulties when those with ADHD perform repetitive tasks that involve little or no reinforcement (Barber, Milich, & Welsh, 1996; Barkley, 1990; Douglas, 1972, 1983, 1988). Written productivity in arithmetic tasks, in particular, may be taken as a measure of persistence; those with ADHD are often found to be less productive on such tasks than control children (Barkley, DuPaul, et al., 1990). Multiple studies also have documented an impairment in persistence of effort in laboratory tasks with children with ADHD (August, 1987; Barber et al., 1996; Borchering et al., 1988; Douglas & Benezra, 1990; Milich, in press; van der

Meere, Hughes, et al., 1995; Wilkison, Kircher, McMahon, & Sloane, 1995). Thus, the evidence for difficulties in the self-regulation of motivation (effort) in those with ADHD is fairly impressive.

It is possible that this component of the model (self-regulation of motivation) provides an explanation for the apparent insensitivity to reinforcement reported in some studies of children with ADHD (see Barkley, 1989; Douglas, 1988; Haenlein & Caul, 1987; and Sagvolden, Wultz, Moser, Moser, & Morkrid, 1989, for reviews). Studies that used varying schedules of reinforcement typically found that children with and without ADHD did not differ in their task performances under immediate and continuous reward (Barber et al., 1996; Cunningham & Knights, 1978; Douglas & Parry, 1983, 1994; Parry & Douglas, 1983). In contrast, in some studies when partial reinforcement was introduced, the performance of children with ADHD declined relative to that of children without ADHD (Parry & Douglas, 1983; Freibergs & Douglas, 1969). Just as many studies, however, did not find this decline (Barber et al., 1996; Pelham, Milich, & Walker, 1986) or found that the difficulty of the task moderated the effect (Barber & Milich, 1989). In a similar vein, the performance of children with ADHD during relatively tedious tasks involving little or no reward was often enhanced by the addition of reinforcement, yet so was the performance of children without ADHD (Carlson & Alexander, 1993; Iaboni et al., 1995; Kupietz, Camp, & Weissman, 1976; Pelham et al., 1986; Solanto, 1990; van der Meere, Hughes, Borger, & Sallee, 1995). These findings have been interpreted as suggesting that children with ADHD have a reduced sensitivity to reinforcement (Haenlein & Caul, 1987) or are dominated by immediate reinforcement (Douglas, 1983; Sagvolden et al., 1989). But the similar enhancement of the performance of children without ADHD by reward in some studies has challenged this interpretation (Pelham et al., 1986; Solanto, 1990). Douglas (Iaboni et al., 1995) also did not find the predicted reward dominance effect in those with ADHD.

The model in Figure 1 suggests a more plausible explanation for these results. It focuses on the observations that the performance of children without ADHD is superior to that of those with ADHD under conditions of little or no reward and may be less affected by reductions in schedules of reinforcement depending on the task duration and its difficulty level. This may result from children without ADHD developing the capacity to bridge temporal delays between the elements of behavioral contingencies through the executive functions in the model. Combined with working memory as well as self-directed speech and the rule-governed behavior it permits, the self-regulation of motivation may allow children without ADHD not only to retain the goal of their performance in mind and subvocally encourage themselves in their persistence but also to create the drive necessary for such persistence. This line of reasoning suggests that, across development, the behavior of those with ADHD remains more contingency shaped, or more under the control of the immediate and external sources of reward, than does the behavior of children without ADHD. Children without ADHD are becoming increasingly rule governed and internally controlled. Therefore, it is not that children with ADHD are less sensitive to reinforcement or are dominated by a tendency to seek immediate

rewards. Rather, they have a diminished capacity for self-regulation of motivation (effort) as well as poorer working memory and internalized self-speech, all of which assist with bridging delays in reinforcement and permit the persistence of goal-directed acts despite a dearth of immediate reinforcement for doing so.

Concerning the self-regulation of arousal, some evidence does exist for possible problems in those with ADHD in the regulation of central and autonomic nervous system arousal for meeting task demands. Multiple reviews of the psychophysiological (Brand & van der Vlugt, 1989; Hastings & Barkley, 1978; Klorman et al., 1988; Rosenthal & Allen, 1978; Rothenberger, 1995) and cognitive (Douglas, 1983, 1988) literatures have concluded that children with ADHD show greater variability in central and autonomic arousal patterns and seem underreactive to stimulation in evoked response paradigms, particularly in the later P300 features of the evoked response. These P300 characteristics have been shown to be associated with frontal lobe activation (Klorman, 1992; Klorman et al., 1988; Knights et al., 1995). Children with ADHD, relative to control groups, have also been shown to display less anticipatory activation on electroencephalograms in response to impending events within tasks, known as the contingent negative variation (CNV) or "expectancy" wave (Hastings & Barkley, 1978), and to have less recruiting of psychophysiological activity over the frontal regions when necessary for appropriate task performance (Brand & van der Vlugt, 1989; Rothenberger, 1995). Studies that used positron emission tomography (PET) to measure brain activity also found diminished brain activation in adults as well as in adolescent girls with ADHD (Ernst et al., 1994; Zametkin et al., 1990). Results obtained with adolescent boys were more equivocal (Zametkin et al., 1993). Similarly, studies that used cerebral blood flow to measure brain activity found decreased perfusion of the frontal regions and striatum in those with ADHD (Lou et al., 1984, 1989; Seig et al., 1995). The evidence available to date is certainly suggestive of problems in the regulation of arousal or activation in those with ADHD, with much of this evidence implicating frontal lobe underactivity.

### *Internalization of Speech*

The association of uninhibited behavior with less mature self-directed speech, rule governance of behavior, and moral reasoning, as stipulated in Figure 1, has been suggested in studies of school children (Kochanska et al., 1994; Weithorn & Kagen, 1984; Zelazo et al., 1995). The few studies dealing with these issues in hyperactivity or ADHD have also found such an immaturity (Berk & Potts, 1991; Copeland, 1979; Gordon, 1979; Rosenbaum & Baker, 1984). Furthermore, children with ADHD are less compliant with directions and commands given by their mothers than are those without ADHD (see Danforth, Barkley, & Stokes, 1991, for a review). Children with ADHD are also less able to restrict their behavior in accordance with experimenter instructions to do so during lab playroom observations when rewarding activities are available for not doing so (see Luk, 1985, for a review). And in studies noted earlier, children with ADHD were found to be much less able to resist forbidden temptations than were same-age peers without ADHD. Such

rule following seems to be particularly difficult for children with ADHD when the rules compete with rewards available for rule violation (Hinshaw et al., 1992, 1995). These results might indicate problems with the manner in which rules and instructions control behavior in children with ADHD.

Further evidence consistent with delayed rule-governed behavior comes from studies showing that children with ADHD are less adequate at problem solving (Douglas, 1983; Hamlett, Pellegrini, & Conners, 1987; Tant & Douglas, 1982) and are also less likely to use organizational rules and strategies in their performance of memory tasks (August, 1987; Douglas & Benezra, 1990; Voelker, Carter, Sprague, Godowski, & Lachar, 1989), particularly where effort must be applied in doing so (Butterbaugh et al., 1989). Problem solving and the discovery of such strategies may be a direct function of rule-governed behavior (Cerutti, 1989). Similar deficits have also been noted in patients with prefrontal injuries (Delis et al., 1992; Verin et al., 1993).

Consistent with the predictions of Hayes (1989) noted earlier concerning the specific effects of rule governance on behavior, children with ADHD seem to (a) demonstrate significantly greater variability in patterns of responding to laboratory tasks, such as those involving reaction time or continuous performance tests (see Corkum & Siegel, 1993; Douglas, 1983; and Douglas & Peters, 1979, for reviews; van der Meere & Sergeant, 1988b, 1988c; Zahn et al., 1991); (b) perform better under conditions of immediate versus delayed rewards; (c) have significantly greater problems with task performance when delays are imposed within the task and as these delays increase in duration; (d) display a greater and more rapid decline in task performance as contingencies of reinforcement move from being continuous to intermittent; and (e) show a greater disruption in task performance when noncontingent consequences occur during the task (see Barkley, 1989; Douglas, 1983; Haenlein & Caul, 1987; and Sagvolden et al., 1989, for reviews; see also Douglas & Parry, 1994; Freibergs & Douglas, 1969; Parry & Douglas, 1983; Schweitzer & Sulzer-Azaroff, 1995; Sonuga-Barke, Taylor, & Hepinstall, 1992; Sonuga-Barke, Taylor, Sembi, & Smith, 1992; Zahn et al., 1991). The difficulties that children with ADHD have working for delayed rewards in delay-of-gratification tasks have also been previously noted (Rappoport et al., 1986).

However, as discussed earlier, others have not found evidence for d above—that partial reinforcement schedules are necessarily detrimental to the task performances of children with ADHD relative to their performance under continuous reinforcement (Barber et al., 1996; Cunningham & Knights, 1978; Douglas & Parry, 1983; Pelham et al., 1986). Instead, the schedule of reinforcement appears to interact with task difficulty in determining the effect of reinforcement on performance by children with ADHD (Barber & Milich, 1989). It is also possible, as suggested earlier, that differences in the delay periods between reinforcement contribute to these inconsistent findings; if delay intervals are sufficiently brief, no differences between children with ADHD and without ADHD under partial reinforcement should be noted. So studies of reinforcement schedules and children with ADHD cannot be interpreted in any straightforward fashion as supportive of the view that poor rule-governed

behavior underlies any problem children with ADHD may have with partial reinforcement schedules. As noted above, Barber et al. (1996) suggested that an inability to sustain effort over time may better explain these findings. And so these results seem more suggestive of poor self-regulation of motivation.

Children with ADHD have been shown to have more difficulty spontaneously developing a strategy to organize material to be memorized (August, 1987). Even after being given an organizational rule to follow and initially benefiting from its usage in the task, children with ADHD eventually decline in their adherence to the strategy in later trials (August, 1987). Similarly, Conte and Regehr (1991) found that hyperactive children had more difficulties with transferring initially learned rules to new learning tasks and required more hints to aid in the transfer. Both studies imply a problem with the manner in which rules are extracted and deployed by children with ADHD in governing their own behavior. Comparable difficulties have also been noted in patients with prefrontal lobe injuries (Gershberg & Shimamura, 1995; Kesner, Hopkins, & Fineman, 1994).

Figure 1 indicates that internalized speech contributes to moral reasoning, probably in concert with the retrospective and prospective functions of working memory. Consistent with this model, delays in moral development, especially if characterized by hedonistic moral reasoning, have been found to be significantly predictive of disruptive and aggressive classroom behavior, diminished social competencies, and, consequently, diminished social status (Bear & Rys, 1994). Moral reasoning also has been shown to be less well developed in hyperactive-impulsive children or those with ADHD (Hinshaw, Herbsman, Melnick, Nigg, & Simmel, 1993; Nucci & Herman, 1982). That this is due to deficient internalization of speech is less certain.

### *Reconstitution*

Within the domain of verbal behavior, tests of verbal fluency, confrontational story narratives or writing, joint peer communication tasks, or other situations and tasks that demand the accurate and efficient communication of information should reflect the process of reconstitution. This process should also be evident in nonverbal behavior and in problem-solving tasks requiring complex and novel motor sequences or goal-directed behavioral creativity. This facility for the creation of multiple novel, complex alternative response sequences, whether in language or motor behavior, is often impaired in patients with damage to the prefrontal lobes (Fuster, 1989, 1995; Milner, 1995; Stuss & Benson, 1986).

The model in Figure 1 predicts that those with ADHD also should manifest greater difficulties with tasks, settings, and interpersonal interactions in which reconstitution is essential. There is evidence suggestive of just such deficiencies within the domain of verbal behavior and discourse in those with ADHD. Children with ADHD have been noted to perform more poorly on tests of simple verbal fluency (Carte et al., in press; Grodzinsky & Diamond, 1992), although others have not documented such differences (Fischer, Barkley, Edelbrock, & Smallish, 1990; Loge, Staton, & Beatty, 1990; McGee et al., 1989; Weyandt & Willis, 1994). The discrepancy in findings may pertain, in part, to the type of fluency test used. Tests in which partici-

pants generate words within semantic categories (Weyandt & Willis, 1994), such as names for animals or fruits, are easier and so are not as likely to discriminate between children with ADHD and controls as are those that use more subtle organizing cues, such as letters (Grodzinsky & Diamond, 1992). Age may also be a factor given that older children with ADHD may have far fewer difficulties on such simple fluency tests than younger children with ADHD (Grodzinsky & Diamond, 1992; Fischer et al., 1990). Low statistical power and the use of nonclinical samples (Loge et al., 1990; McGee et al., 1989) could also have contributed to the inconsistencies in results across studies. So it is not clear as yet that simple word fluency is impaired in children with ADHD.

Studies of more complex language fluency and discourse organization, however, have been more likely to reveal problems in children with ADHD. Children with ADHD, compared with those without ADHD, appear to produce less speech in response to confrontational questioning (Tannock, 1996; Ludlow, Rapoport, Bassich, & Mikkelsen, 1980), are less competent in verbal problem-solving tasks (Douglas, 1983; Hamlett et al., 1987), and are less capable of communicating task-essential information to peers in cooperative tasks (Whalen, Henker, Collins, McAuliffe, & Vaux, 1979). They also produce less information and less organized information in their story narratives (Tannock, 1996; Tannock et al., 1992; Zentall, 1988) and in describing their own strategies used during task performance (Hamlett et al., 1987). When no goal or task is specified, the verbal discourse of children with ADHD does not appear to differ from that of children without ADHD (Barkley et al., 1983; Zentall, 1988). I could find no studies of nonverbal motor or gestural fluency and behavioral simulation in children with ADHD, however, so the predictions of the model for this domain of reconstitution remain untested.

The evidence for a deficit in behavioral or verbal creativity, as opposed to fluency, is considerably weaker, primarily because so few researchers have examined the issue as well as because of problems in the very definition of creativity itself (Brown, 1989). Creativity during free play (Alessandri, 1992) and performance of nonverbal, figural creativity tasks (Funk, Chessare, Weaver, & Exley, 1993) have been noted to be significantly below normal levels in children with ADHD. However, Shaw and Brown (1990) did not find a deficit in creativity in a small sample of high-IQ children with ADHD. They did find that those with ADHD gathered and used more diverse, nonverbal, and poorly focused information and displayed higher figural creativity. The use of so small a sample and of only bright children with ADHD, however, hardly makes for a reasonable test of this prediction. More research on creativity in ADHD is clearly needed.

### *Motor Control-Fluency-Syntax*

Inhibition and the executive functions described in Figure 1 contribute greater control, timing, persistence, flexibility, novelty, complexity, and syntax to motor actions that are goal directed (Fuster, 1989, 1995). These effects may assist with the development of ever finer, more varied and complex, and more hierarchically organized patterns of motor responses directed

toward goals. Some evidence exists for a linkage of behavioral inhibition with this type of motor control. In the research literature on ADHD, motor problems also have been noted (Barkley, DuPaul, et al., 1990; Hartsough & Lambert, 1985; Stewart, Pitts, Craig, & Dieruf, 1966; Szatmari, Offord, & Boyle, 1989), but they have rarely been discussed for their theoretical implications except, perhaps, by Denckla (1985). Neurological examinations for "soft" signs related to motor coordination and motor overflow movements find children with ADHD to demonstrate more such signs and movements than control children, including those with purely learning disabilities (Carte et al., in press; Denckla & Rudel, 1978; Denckla, Rudel, Chapman, & Krieger, 1985; McMahon & Greenberg, 1977; Shaywitz & Shaywitz, 1984; Werry et al., 1972). These overflow movements have been interpreted as indicators of delayed development of motor inhibition (Denckla et al., 1985).

Studies that used tests of fine motor coordination, such as balance, fine motor gestures, electronic or paper-and-pencil mazes, and pursuit tracking, often found children with ADHD to be less coordinated in these actions than controls (Hoy, Weiss, Minde, & Cohen, 1978; Mariani & Barkley, in press; McMahon & Greenberg, 1977; Moffitt, 1990; Shaywitz & Shaywitz, 1984; Ullman et al., 1978). Simple motor speed, as measured by finger-tapping rate or grooved pegboard tests, does not seem to be as affected in children with ADHD as is the execution of complex, coordinated sequences of motor movements (Barkley et al., in press; Breen, 1989; Grodzinsky & Diamond, 1992; Mariani & Barkley, in press; Seidman et al., 1995, 1996). The bulk of the available evidence, therefore, supports motor control deficits in ADHD.

But the most rigorous and compelling body of evidence for a motor control deficit in ADHD comes from the substantial programmatic research of Sergeant, van der Meere, and their colleagues in Holland (Sergeant, 1995a). Using an information-processing paradigm, these researchers have isolated the cognitive deficit in those with ADHD to the motor control stage rather than to an attentional or information-processing stage. More specifically, their research suggests that the deficit is not at the response choice stage but at the motor presetting stage involved in motor preparedness to act (Oosterlaan & Sergeant, 1995). Fuster (1989) identified this type of motor preparedness, or anticipatory set, as one of the major effects that the executive functions would have on motor control. But he also identified a sensitivity to errors or response feedback as being a second influence the executive functions would have over the motor control system. Deficits in behavioral inhibition should lead to an insensitivity to errors and to a loss of behavioral flexibility as a consequence (Fuster, 1995; Knights et al., 1995; Milner, 1995). As noted earlier, research has also identified such an insensitivity in children with ADHD (Oosterlaan & Sergeant, 1995; Sergeant & van der Meere, 1988).

Complex motor sequencing and the generating of complex, novel motor responses as well as their syntax have not received much attention in research on ADHD. Handwriting, however, is just such a complex sequencing of simpler motor movements built into complex, novel patterns of new arrangements of letters, words, and sentences that requires great flexibility and fluency of fine motor movement. Handwriting has often been

noted in the clinical literature (Sleator & Pelham, 1986) to be less mature in those with ADHD. Difficulties with drawing have likewise been found in children with ADHD (Hoy et al., 1978; McGee, Williams, & Feehan, 1992). And those with ADHD have been found to be more likely to have speech problems relative to controls (Barkley, DuPaul, et al., 1990; Hartsough & Lambert, 1985; Munir, Biederman, & Knee, 1987; Szatmari et al., 1989; Taylor et al., 1991). All of these findings might imply problems with the programming and rapid execution of complex, fine motor sequences in those with ADHD.

One test that seems to capture a simpler form of motor sequencing is the Hand Movements Test from the Kaufman Assessment Battery for Children (Kaufman & Kaufman, 1983). Patients with frontal lobe injuries have difficulties with such tasks (Kesner et al., 1994). Three studies have used this task in the study of ADHD, and all found the ADHD group to be significantly less proficient than the non-ADHD group (Breen, 1989; Grodzinsky & Diamond, 1992; Mariani & Barkley, in press), which suggests a problem with temporal ordering of motor sequences in those with ADHD (Kesner et al., 1994). The developers of the test battery also commented that hyperactive children performed poorly on this task during the clinical validation trials of the battery (Kaufman & Kaufman, 1983). This could reflect the children's simply having a problem with the working memory demands of this task. However, other research discussed above that involved motor tasks with few or no working memory demands still found motor control deficits in ADHD.

### The Place of Inattention in the Model

The executive function deficits discussed in the previous sections can account for the appearance of inattention seen in ADHD despite the fact that research has not identified a deficit in attention in these children. The model also explains the rather dramatic fluctuation in symptoms across settings and tasks. The poor sustained attention that apparently characterizes those with ADHD probably represents an impairment in goal- or task-directed persistence arising from poor inhibition and the toll it takes on self-regulation. And the distractibility ascribed to those with ADHD most likely arises from poor interference control that allows other external and internal events to disrupt the executive functions that provide for self-control and task persistence. The net effect is an individual who cannot persist in effort toward tasks that provide little immediate reward and who flits from one uncompleted activity to another as disrupting events occur. The inattention in ADHD can now be seen as not so much a primary symptom as a secondary one; it is a consequence of the impairment that poor behavioral inhibition and interference control create in the self-regulation or executive control of behavior.

This line of reasoning suggests a critical distinction between two forms of sustained attention (persistence); that distinction is between persistence that is contingency-shaped and that which is self-regulated and goal directed. The former is largely a function of immediate contextual factors, such as the schedule of reinforcement associated with the task, the novelty of the task, and the close temporal contiguity of the elements of the contingency. The second type of sustained attention arises as an emer-

gent property out of the interactions of the executive functions discussed above that permit self-regulation and control over the motor system. This form of persistence is controlled by internally represented information that permits much longer, more complex, and novel chains of responses to be created and executed in the achievement of later goals. These behavioral structures do not require immediate reward for execution because the motivation driving them is self-created. And it is this self-regulatory type of sustained attention that is probably developmentally delayed in children with ADHD, not the type that is contingency shaped. So long as immediate and frequent reinforcement is available in the context for persisting in performing responses, those with ADHD should be less or even not distinguishable from those without ADHD. But those with ADHD should become increasingly distinct from those without ADHD when tasks and settings demand that longer chains of behaviors be strung together to achieve more temporally distant consequences in the absence of immediate consequences for doing so. This explanation clarifies why the "inattentive" symptoms are found to form a separate but only semi-independent dimension from hyperactive-impulsive behavior in parent-teacher ratings. The inattention (impersistence) is at least one step (or more) removed from the problems with behavioral inhibition through the intermediary constructs of working memory and the other executive functions. It is also this self-regulated form of attention that should prove to be qualitatively distinct from the type of inattention seen in children with the predominantly inattentive type of ADHD. The latter children, as discussed earlier, likely have a deficiency in focused or selective attention that is not related to problems with behavioral inhibition and self-regulation.

Some evidence already exists to support a distinction between goal-directed persistence (internal or self-dependent) and contingency-shaped (context-dependent) sustained attention as well as the association of the former with poor inhibitory control. Shoda et al. (1990) found that preschool children's ability to inhibit responding in a resistance-to-temptation task significantly predicted parent ratings of those same children's later concentration, sustained attention, and distractibility at adolescence. Measures of working memory, such as delayed spatial memory, mental arithmetic, digit span, and reproduction of hand movement sequences, have been found to correlate with tests and behavioral observations frequently interpreted as measuring sustained attention and behavioral persistence in preschool children with ADHD (Mariani & Barkley, in press). Levy and Hobbes (1989), likewise, found that a measure of vigilance (a card-playing task) loaded on the same factor as a measure of working memory (related to spelling ability) and that this factor significantly distinguished their ADHD and control groups. These studies suggest links between inhibition, working memory, and persistence or sustained attention.

### Developmental Considerations

Research on the components of this theory should find that response inhibition and the neuropsychological processes dependent on it are deficient in their development in those with ADHD. Each executive function most likely represents a semi-

independent neuropsychological system that falls along a continuum of normal functioning and interacts with the other executive functions in producing self-regulation. The degree of delay in these functions would vary in severity partly as a function of the degree of ADHD (disinhibition). And each executive function probably emerges at separate times in development rather than all executive functions emerging simultaneously (Bronowski, 1977). Illustrating this differential timing for the development of these executive functions is the work of Levin et al. (1991), who found significant increases in sensitivity to feedback, problem solving, concept formation, and impulse control between groups of children without ADHD 7–8 years old and 9–12 years old. Further significant developmental advances were noted in memory strategies, memory efficiency, planning time, problem solving, and hypothesis seeking between similar groups of children 9–12 years old and 13–15 years old. Similarly, Welsh et al. (1991) and Passler, Isaac, and Hynd (1985) found that, whereas organized strategic and planful behavior was detected as early as Age 6, more complex search behavior and hypothesis testing matured by Age 10, and verbal fluency, motor sequencing, and complex planning abilities had not reached adult-level performances by Age 12. It would not be difficult to reinterpret these findings in terms of the executive functions in Figure 1. Kopp (1989) has set forth an explanation of the development of emotional self-regulation that is also quite consistent with the present model.

Were test batteries of the executive functions given to children with ADHD, the theory presented here would predict that, at each age level studied, children with ADHD would perform like younger children without ADHD. They would show a pattern of development otherwise similar to that of children without ADHD in shape and trajectory. This already seems evident in the findings of studies of different ages of those with ADHD and those without ADHD on tests of executive functions (Barkley et al., 1992; Grodzinsky & Diamond, 1992; Pennington & Ozonoff, 1996). These studies were cross-sectional, however, which limits the degree to which inferences about true developmental processes can be made.

#### Unresolved Issues

An important issue deserving of research and critical to the model is the extent to which the deficits in inhibition and its associated executive functions are specific to ADHD or result from disorders often coexisting with it, such as aggression (oppositional defiant disorder) and conduct disorder or, less often, learning disabilities. Few of the studies on ADHD cited here attempted to disentangle these effects. Some of the more recent studies did so, however, and their findings suggest that these cognitive disturbances are more closely associated with ADHD than with these other disorders (Pennington & Ozonoff, 1996).

Research suggests that impairment in behavioral inhibition is more characteristic of children with ADHD than of those with academic underachievement, emotional disturbance, conduct disorder, or autism (Milich et al., 1994; Pennington & Ozonoff, 1996; Schachar & Logan, 1990; Werry, Elkind, & Reeves, 1987). Likewise, the disturbance in the motor inhibition, pre-setting, effort, and control stages of information-processing par-

adigms are specific to children with ADHD and are not seen in those without ADHD but with anxiety or pure aggression (Oosterlaan & Sergeant, 1995). Direct observations of playroom behavior have also shown that problems with impulsive, undercontrolled behavior and adherence to rules to restrict behavior are more characteristic of children with ADHD than of aggressive children (Milich et al., 1982). These and other studies (Werry et al., 1987) also seem to show that children with mixed ADHD and conduct problems are likely to have as many or more cognitive impairments than those with ADHD alone. And the difficulties with motor control, response perseveration, rule following, and verbal fluency have likewise been shown to be associated more with ADHD than with purely aggressive behavior (Carte et al., in press; McBurnett et al., 1993; Seidman et al., 1995, 1996; Werry et al., 1987). As other reviews have concluded (Hinshaw, 1987; Pennington & Ozonoff, 1996; Taylor et al., 1991; Werry, 1988), ADHD is most closely associated with cognitive impairments, whereas conduct disorder is more aligned with adverse child-rearing variables and social disadvantage. Similarly, studies that used control groups of children with reading disabilities or more generally learning disabilities did not find such children to demonstrate the inhibitory or executive function deficits characteristics of those with ADHD (Barkley, DuPaul, et al., 1990; Dykman & Ackerman, 1992; Epstein, Shaywitz, Shaywitz, & Woolston, 1992; Pennington & Ozonoff, 1996). Thus, although it is hardly definitive, what research does exist places the inhibitory, neuropsychological, and motor deficits described here in the domain of ADHD rather than in the domain of aggression–conduct problems or learning disabilities. Still unresolved, however, is whether the group with mixed ADHD and conduct problems has a qualitatively different disorder, as some have suggested (Biederman et al., 1992; Schachar & Logan, 1990), or just a more severe form of the same disorder as those with ADHD alone.

There are numerous other unresolved issues related to this hybrid model of executive functions and ADHD that speak to its present limitations and the need for future research. These issues include determining (a) the precise strength of the relationship between behavioral inhibition and each of the executive functions; (b) the precise degree to which each executive function contributes to the motor control module in the model; (c) the extent to which the subfunctions placed within each component of the model are best placed where they are now; (d) whether there is some hierarchical organization to these four executive functions; (e) whether the number of components of the model can be further reduced (i.e., Is self-directed speech the source of verbal working memory, as current research implies?; Becker, 1994); (f) whether all four executive functions represent a larger process of the internalization and self-direction of all human behavior generally rather than just that of speech (i.e., self-directed seeing, hearing, manipulation, etc.); (g) the developmental and sequential staging of these executive functions; (h) the degree to which each executive function and its subfunctions are impaired by the behavioral inhibition deficit in ADHD; (i) the degree to which stimulant medications differentially affect each of these domains of executive functions and motor control in ADHD; (j) whether the predominantly inattentive type of ADHD can be dissociated from the remaining



hyperactive-impulsive types on measures of these executive functions; (k) the manner in which socialization influences the development and organization of these executive functions; and (l) the potential gender and cultural differences that may exist in the development of these executive functions and in their deficiencies in those with ADHD.

### Conclusion

The present theory holds that the satisfactory development of inhibition is essential for the normal performance of five other neuropsychological abilities: working memory, internalization of speech, self-regulation of affect-motivation-arousal, reconstitution, and motor control-fluency-syntax. The first four of these are considered executive in nature because they permit self-regulation, the control of behavior by internally represented information, and the cross-temporal organization of behavior. Such self-regulation gives rise to the direction and persistence of behavior toward future goals and the ability to re-engage that behavior if disrupted. This intentional, purposive form of goal-directed behavior apparently functions to maximize future consequences over immediate ones for the individual. So behavioral inhibition is linked to working memory and sense of time, internalization, self-motivation, behavioral creativity, and self-control more generally. Besides its immediate application here to the understanding of ADHD, the hybrid model shown in Figure 1 would seem to have significant explanatory power within both neuropsychology and developmental psychology, perhaps helping to bridge these literatures with respect to the concepts of executive functions and self-regulation.

Substantial evidence points to an impairment in three processes involving behavioral inhibition in ADHD: inhibition of prepotent responses, stopping of ongoing responses given feedback on errors, and interference control. When the hybrid model of executive functions discussed above is extended to ADHD, impairments are predicted in the four executive functions in those having this disorder. These executive deficits then create deficiencies in motor control-fluency-syntax or the control of motor behavior by internally represented information. Research findings on ADHD, to varying degrees, seem to be consistent with deficits in the components of the model. The most consistent evidence to date appears to support the components of behavioral inhibition, working memory, poor self-regulation of motivation, and motor control and sequencing. It is not so much that the remaining components (internalized speech and reconstitution) have gone unsupported but that they have been less studied in ADHD. The few researchers who have ventured to examine them have produced suggestive evidence that these components may also be impaired in ADHD.

Much of the literature that does exist on the cognitive or neuropsychological deficits in ADHD suffers from numerous methodological problems. Most significant among these would have to be (a) the use of such small sample sizes that there is inadequate statistical power for detecting the small to moderate effect sizes that are probably associated with deficits in these executive functions; (b) the use of inconsistent selection criteria across studies in defining ADHD; (c) the failure to control for potentially confounding comorbid disorders; (d) the lack of

attention to maturational and gender effects; and (e) the lack of regard for the effects of family history of ADHD on the deficits associated with ADHD in children. Such procedural compromises make much of the extant research inadequate for testing and potentially falsifying the predictions of the present model. Better designed research should help to resolve these inconsistencies and will undoubtedly lead to modifications of the model presented here.

The hybrid model of executive functions developed here and the impairments it predicts in those with ADHD point to a large number of additional avenues for future investigation. These may yield new and important information on both the nature of executive functions and self-regulation as well as on the nature of ADHD itself. Such theory-driven research is to be welcomed into the science of ADHD and should offer much promise for improving the understanding and treatment of those with the disorder.

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# Larger deficits in brain networks for response inhibition than for visual selective attention in attention deficit hyperactivity disorder (ADHD)

James R. Booth,<sup>1,2,3</sup> Douglas D. Burman,<sup>1</sup> Joel R. Meyer,<sup>2</sup> Zhang Lei,<sup>4</sup>  
Barbara L. Trommer,<sup>5</sup> Nicholas D. Davenport,<sup>1</sup> Wei Li,<sup>2</sup> Todd B. Parrish,<sup>3,6</sup>  
Darren R. Gitelman<sup>3,7</sup> and M. Marsel Mesulam<sup>3,7</sup>

<sup>1</sup>Department of Communication Sciences and Disorders, Northwestern University, Evanston, IL, USA; <sup>2</sup>Department of Radiology, Evanston Northwestern Healthcare, Evanston, IL, USA; <sup>3</sup>Cognitive Neurology and Alzheimer's Disease Center, Northwestern University, Chicago, IL, USA; <sup>4</sup>fMRI Research Center, 306 Hospital, Beijing, P.R. China; <sup>5</sup>Department of Pediatric Neurology, Evanston Northwestern Healthcare, Evanston, IL, USA; <sup>6</sup>Department of Radiology, Northwestern University Medical School, Chicago, IL, USA; <sup>7</sup>Department of Neurology, Northwestern University Medical School, Chicago, IL, USA

**Background:** Brain activation differences between 12 control and 12 attention deficit hyperactivity disorder (ADHD) children (9- to 12-year-olds) were examined on two cognitive tasks during functional magnetic resonance imaging (fMRI). **Method:** Visual selective attention was measured with the visual search of a conjunction target (red triangle) in a field of distracters and response inhibition was measured with a go/no-go task. **Results:** There were limited group differences in the selective attention task, with control children showing significantly greater intensity of activation in a small area of the superior parietal lobule region of interest. There were large group differences in the response inhibition task, with control children showing significantly greater intensity of activation in fronto-striatal regions of interest including the inferior, middle, superior and medial frontal gyri as well as the caudate nucleus and globus pallidus. **Conclusion:** The widespread hypoactivity for the ADHD children on the go/no-go task is consistent with the hypothesis that response inhibition is a specific deficit in attention deficit hyperactivity disorder. **Keywords:** ADD/ADHD, attention, brain development, brain imaging, development, inhibition.

Attention deficit hyperactivity disorder (ADHD) is one of the most common forms of childhood disorder in the United States. The estimates of prevalence are about 5–15% of school-age children (Szatmari, 1992; Wolraich, Hannah, Baumgaertel, & Feurer, 1998). About 50% of these children continue to experience ADHD symptoms when they are adults (Mannuzza, Klein, Bessler, Malloy, & LaPadula, 1993; Weiss & Hechtman, 1979) with about 2–3 times as many males as females affected (Gaub & Carlson, 1997; Wolraich et al., 1996). Two of the central deficits in ADHD are response inhibition and selective attention. Barkley (1997) argues that poor interference control and poor inhibition are the primary deficits in ADHD and that these result in deficits in sustained attention and executive functions (Barkley, 1997).

Over the last several years the neural basis of response inhibition and selective attention has become clearer through the use of neuroimaging technology. Casey, Durston, and Fossella (2001) have argued that the prefrontal cortex is involved in interference control and that the basal ganglia is involved in response inhibition (Casey et al., 2001). The prefrontal region seems to be involved in the supporting representations of relevant information from interference due to competing information (Miller & Cohen, 2001), whereas the basal ganglia seems to be

involved in the inhibition of inappropriate behaviors (Mink, 1996). The visual selective attention network is partially distinct from the response inhibition network. Mesulam (1990, 1999) has proposed that the superior parietal lobule and the lateral premotor cortex form the core of the network for selective attention. The superior parietal lobule appears to be involved in representing extrapersonal space and the lateral pre-motor cortex seems to be involved in orienting and exploratory movements. Many studies have demonstrated that the superior parietal lobule and the lateral premotor cortex are active in both overt and covert selective attention tasks (Corbetta, 1998; Gitelman et al., 1999; Kim et al., 1999; Nobre, Gitelman, Dias, & Mesulam, 2000).

Several lines of behavioral and molecular genetic work show a genetic component for ADHD involving the dopaminergic system (Comings et al., 2000; Cook, Stein, & Krasowski, 1995; Faraone, Doyle, Mick, & Biederman, 2001; Gill, Daly, Heron, Hawi, & Fitzgerald, 1997; LaHoste, Swanson, & Wigal, 1996; Swanson et al., 2000). Furthermore, one of the most common medications for ADHD, methylphenidate, seems to act on the brain by amplifying dopamine signals (Volkow, Fowler, Wang, Ding, & Gatley, 2002; Volkow et al., 2001). These findings suggest that one of the primary brain deficits in ADHD may lie in fronto-striatal brain networks involving the

prefrontal region and the basal ganglia. Indeed, structural and functional neuroimaging research shows differences between control and ADHD subjects in this network. ADHD subjects have smaller prefrontal volumes than controls (Castellanos et al., 1996; Yeo et al., 2003) and studies have documented relations between prefrontal morphology and behavioral characteristics in ADHD subjects (Casey, Castellanos, Giedd, & Marsh, 1997a; Castellanos et al., 2002; Filipek et al., 1997). Functional studies have also generally shown less activation in ADHD subjects compared to controls in frontal and cingulate regions (Amen & Carmichael, 1997; Bush et al., 1999; Ernst, Zametkin, Matochik, Jons, & Cohen, 1998a; Rubia et al., 1999, 2001; Zametkin et al., 1990) and have shown correlations between activation and behavioral characteristics in ADHD subjects (Teicher et al., 2000; Yeo et al., 2003; Zametkin et al., 1993).

Frontal regions are heavily interconnected with striatal regions, and neuroimaging research has shown differences between control and ADHD subjects in these subcortical structures. Although some studies show larger caudate volumes in ADHD subjects (Mataro, Garcia Sanchez, Junque, Estevez, & Pujol, 1997), most studies show that ADHD subjects have smaller caudate and globus pallidus volumes (Aylward et al., 1996; Castellanos et al., 1996, 2002; Filipek et al., 1997; Hynd et al., 1993) and studies have shown that volume and asymmetry of the caudate nucleus are correlated with task performance on response inhibition tasks in ADHD subjects (Casey et al., 1997a; Semrud-Clikeman et al., 2000). Functional neuroimaging studies have also reported differences in the amount of activation in the caudate, putamen and globus pallidus (Durstun et al., 2003; Ernst, Cohen, Liebenauer, Jons, & Zametkin, 1997; Jin, Zang, Zeng, Zhang, & Wang, 2001; Rubia et al., 1999, 2001; Vaidya et al., 1998). In summary, the literature clearly shows that there are pronounced differences between control and ADHD subjects in the network involved in interference control and response inhibition.

In contrast to the extensive work on the fronto-striatal system, comparatively little neuroimaging research has reported brain differences in the selective attention network. Filipek et al. (1997) showed that ADHD subjects have smaller white matter tracts than controls in posterior brain regions and that methylphenidate non-responders had smaller bilateral retrocallosal (parietal) white matter tracts than responders (Filipek et al., 1997). Castellanos et al. (2002) reported that ADHD had smaller parietal as well as fronto-striatal (caudate) volumes, but only the frontal-striatal volumes correlated with clinician and parent ratings of symptom severity. A positron emission tomography (PET) study has supported these structural studies by showing abnormalities in glucose metabolism in posterior parietal regions (Ernst et al., 1997).

Although event-related potential (ERP) studies have also consistently found differences between ADHD and controls, it is difficult to determine the focus of activation due to low spatial resolution. Most ERP studies report smaller amplitude in centro-parietal potentials at around 300 ms after stimulus onset (Brandeis et al., 1998; Karayanidis et al., 2000; Robaey, Breton, Dugas, & Renault, 1992; van Leeuwen et al., 1998) and the amplitude of this component in ADHD subjects can be normalized with methylphenidate treatment (Jonkman et al., 1997; Verbaten et al., 1994; Winsberg, Javitt, & Shanahan/Silipo, 1997).

This review of the literature suggests that ADHD subjects tend to have larger abnormalities in the response inhibition network (including prefrontal cortex and basal ganglia) than in the selective attention network (including superior parietal lobule and lateral premotor cortex). Behavioral research also seems to suggest that there are larger deficits for ADHD subjects in response inhibition than in selective attention. Several studies have consistently shown that ADHD subjects are slower and exhibit more errors on go/no-go tasks (Castellanos et al., 2000; Hartung, Milich, Lynam, & Martin, 2002; Iaboni, Douglas, & Baker, 1995; Itami & Uno, 2002; Vaidya et al., 1998; Yong-Liang et al., 2000). In contrast, studies have inconsistently shown differences between ADHD and controls on tasks tapping into selective attention. Two studies have shown that the slope of reaction time as function of number of stimuli in a memory search task was the same for ADHD and controls (Klorman, Brumaghim, Fitzpatrick, & Borgstedt, 1992; Sergeant & Scholten, 1983) and another study showed no group differences with respect to task efficiency in a distraction condition during a focused attention task that required ignoring irrelevant information in favor of relevant information (van der Meere & Sergeant, 1988). Furthermore, no difference between ADHD and controls were found in latency or accuracy of visuo-spatial memory in a task that required subjects to delay their saccadic eye movement to a visually presented cue (Ross, Hommer, Breiger, Varley, & Radant, 1994). Other studies have shown reliable differences between ADHD and controls in the initiation of visual search and the slope of the visual search function (Karatekin & Asarnow, 1998). Although [Leung and Connolly \(1994\)](#) also showed deficits in a visual search task, they showed that the performance decrement over time was similar in ADHD and controls ([Leung & Connolly, 1994](#)). One study has directly compared deficits in response inhibition to selective attention (Aman, Roberts, & Pennington, 1998). They found that ADHD children had larger deficits on 'frontal lobe' tasks (i.e., Stopping Task, Anti-saccade Task, Tower of Hanoi) than parietal tasks (i.e., Visual-Spatial Cuing Task, Turning Task, Spatial Relations). More studies are needed that directly compare response inhibition

and selective attention within the same population of ADHD children, preferably with experimental tasks that are equated in stimulus characteristics so that observed differences can be attributed clearly to one construct.

The goal of this project was to use fMRI to examine brain activation differences between control and ADHD children (9- and 12-year-olds) in both visual selective attention and response inhibition. No neuroimaging studies have directly compared both selective attention and response inhibition in the same population, so we cannot make statements about the relative role of each of these networks in the disorder. It is important to compare population differences on selective attention and response inhibition tasks in order to examine the hypothesis that response inhibition is the primary deficit in ADHD (Barkley, 1997). In our study, the neural substrate of selective attention was measured by a conjunction visual search task (Treisman, 1990, 1992; Treisman & Gelade, 1980) that has been shown to activate the superior parietal lobule and lateral premotor cortex (Ashbridge, Walsh, & Cowey, 1997; Corbetta, Shulman, Miezin, & Petersen, 1995; Donner et al., 2000; Walsh, Ellison, Ashbridge, & Cowey, 1999). Response inhibition was measured by a go/no-go task that has been shown to activate the basal ganglia and prefrontal cortex (Kawashima et al., 1996; Konishi, 1998; Liddle, Kiehl, & Smith, 2001; Menon, Adleman, White, Glover, & Reiss, 2001; Rubia et al., 2000b; Walddogel, 2000). Both tasks were structured in exactly the same way so as to equate perceptual demands of the tasks except that the visual search task required a yes or no response, whereas the no-go task required the inhibition or execution of a response (target present versus absent for both tasks). Based on the genetic, brain imaging and behavioral research reviewed above, we expected smaller differences between control and ADHD children for selective attention than for response inhibition. Specifically, we expected to find fewer voxels in our regions of interest to exhibit significant differences in intensity of activation between control and ADHD children. These regions included the superior parietal lobule and lateral premotor for the visual search task and the basal ganglia and prefrontal cortex for the response inhibition task.

## Materials and methods

### Participants

Twelve control children ( $M = 10.9$ ; range = 9.3–11.7 years) and twelve ADHD children ( $M = 11.0$ ; range = 9.4–11.9 years) participated in the study. There were 7 males and 5 females in the control group and there were 8 males and 4 females in the ADHD group. Control children were recruited from the Evanston, Illinois community. ADHD children were recruited from pediatric or neurology practices in the Chicago metropolitan area. All ADHD children had been given

the ADHD diagnosis by a medical professional and were currently taking medication (5 Ritalin, 5 Concerta, 1 Adderall and 1 Dexedrine). ADHD children had been on medication between 1 and 3 years. All ADHD children were free from medication for at least 48 hours at the time of the behavioral testing or the MRI scan.

In order to independently confirm the diagnosis of ADHD, the parents of children were administered the Disruptive Behavior Rating Scale (Barkley & Murphy, 1998), which includes modified inattentive and hyperactive-impulsive symptoms from the *Diagnostic Statistical Manual – IV* (American Psychiatric Association, 1994). According to the DSM-IV, a child must have 6 or more symptoms from either scale to qualify for the diagnosis of ADHD. The Disruptive Behavior Rating Scale allows for a graded response on a 4-point Likert scale including the labels ‘never or rarely’, ‘sometimes’, ‘often’ and ‘very often’. In order to compare the Disruptive Behavioral Rating Scale to the DSM-IV, we considered only ‘often’ or ‘very often’ to indicate the presence of that symptom. According to this criterion, all of the ADHD children had at least 6 symptoms on one of the scales: 8 children for both the inattentive and hyperactive-impulsive scales and 4 children for just the inattentive scale. No control children had more than two of the inattentive or hyperactive-impulsive items endorsed ‘often’ or ‘very often’ by their parents.

Parents of children were given an informal interview to insure that they did not meet the following exclusionary criteria: (1) non-English or bilingual backgrounds, (2) uncorrected visual impairment or significant hearing impairment, (3) DSM Axis I or II psychiatric disorders, (4) oppositional defiant disorder or conduct disorder, (5) neurological disease or seizures, (6) severe pregnancy or birth complications, (7) significant head injury with loss of consciousness, (8) chronic substance abuse, and (9) for the control children, not taking medication affecting the central nervous system and no attention deficit hyperactivity disorder.

### Standardized testing

All participants were administered an extensive battery of standardized tests including the full version of the Wechsler Intelligence Scale for Children-III (Wechsler, 1991), Peabody Picture Vocabulary Test-III (Dunn & Dunn, 1997), Woodcock Johnson Picture Vocabulary and Word Attack (Woodcock, 1997), Comprehensive Test of Phonological Processes (Wagner, Torgesen, & Rashotte, 1999), and Wide Range Achievement Test-III (Wilkinson, 1993). The purpose of this battery was to establish that the control and ADHD children were not significantly different on measures of cognitive functioning.

### Functional activation tasks

Both the selective attention and response inhibition task involved red triangle targets that were presented on 50% of the trials. The non-target stimuli (distracters) were blue triangles and red trapezoids; therefore, the red triangle target shared either its shape or its color with each of the distracters. Each stimulus was displayed for 1400 ms followed by an interval (blank screen) that was either 450, 600 or 750 ms. The average

inter-stimulus interval was 2000 ms. A variable interval was used to limit the participants' ability to pace during the task. Participants were encouraged to respond as quickly as possible. Both tasks consisted of 12 blocks and each block consisted of 18 trials plus a one-word instruction screen presented for 3 seconds at the beginning of each block. The selective attention task was always administered before the response inhibition task.

**Selective attention task.** For the selective attention task, blocks with one and nine stimuli were alternated (6 blocks of each). In the blocks with one stimulus, only one shape was presented at a time and each distracter (a blue triangle or red trapezoid) was presented on 25% of the trials. The display was pseudo-randomized to prevent more than three of the same distracters or targets from appearing in consecutive trials. In the blocks with nine stimuli, nine shapes were presented in a  $3 \times 3$  matrix including 4 of each distracter (blue triangles and red trapezoids) plus either a target or another distracter. See Figure 1 for an example of one trial in the nine stimuli condition. The targets were counterbalanced to ensure that each of the nine positions had an equal number of distracters. In order to prevent large regions with similar stimuli, the distracters were also positioned so that there were no more than 3 of the same distracter adjacent on a side. For blocks with one and nine stimuli, the participant pressed his or her index finger if the target was present and the middle finger if the target was absent. An instruction screen was presented for 3 seconds at the beginning of each block and displayed 'One' for the blocks with one stimulus and 'Many' for the blocks with nine stimuli.

**Response inhibition task.** For the response inhibition task, go and no-go blocks were alternated (6 blocks of each). In both blocks, trials consisted of nine stimuli. In the go blocks, the participants pressed their index finger as soon as the shapes appeared on the screen, regardless of whether or not a target was present. In the no-go blocks, the participants pressed their index finger as quickly as possible once stimuli appeared, withholding their finger press only if the target was present. An instruction screen was presented for 3 seconds at the beginning of each block and displayed 'Go' for the go blocks and 'Stop' for the no-go blocks.

Because the same stimuli were used in the selective attention and response inhibition tasks, there was exactly the same amount of search in both tasks. When the target was absent, both tasks required exhaustive search and when the target was present both tasks required search until the target was identified. On average, target identification probably occurred on the middle stimulus in the nine-stimuli array because the targets were equally distributed in the nine positions (assuming a serial left to right and up to down search strategy).

### Experimental procedure

After informed consent was obtained, participants were administered the informal interview (see above) and the practice session (see below). Within three days, the participant was administered the fMRI session. The

Institutional Review Board at Northwestern University and Evanston Northwestern Healthcare Research Institute approved the consent procedures.

**MRI practice session.** The participant was acclimated to the scanner environment in a simulator (Rosenberg et al., 1997). From the tube-like structure, the participant was able to view a computer monitor about 40 cm directly above. The participant put on headphones and grasped a button box in his/her right hand. The experimenter played digitized sounds to familiarize the participant with the loud banging noise made by the MRI machine. After the participant seemed comfortable with the loud sounds in the simulator, the participant practiced a full-length version of each experimental task.

**MRI data acquisition.** After screening, the participant was asked to lie down on the scanner bed. The head position was secured with a specially designed vacuum pillow (Bionix, Toledo, OH). An optical response box (Lightwave Medical, Burnaby, Canada) was placed in the participant's right hand and a squish ball was placed in the left hand. The squish ball was used to signal the operator to terminate the scan if the participant felt that this was necessary for any reason. The head coil was positioned over the participant's head and a goggle system for the visual presentation of stimuli (Avotec, Jensen Beach, FL) was secured to the head coil. Each imaging session took less than one hour.

All images were acquired using a 1.5 Tesla General Electric scanner. Gradient echo localizer images were acquired to determine the placement of the functional slices. For the functional imaging studies, a susceptibility weighted single-shot EPI (echo planar imaging) method with BOLD (blood oxygenation level-dependent) was used. The following scan parameters were used: TE = 40 ms, flip angle =  $90^\circ$ , matrix size =  $64 \times 64$ , field of view = 22 cm, slice thickness = 4 mm (no gap), number of slices = 32. These scanning parameters resulted in a  $3.437 \times 3.437 \times 4$  mm voxel size. The acquisition of a volume (32 slices) of data was repeated every 3 seconds (TR = 3000 ms) for a total of 7.8 minutes per run. This amounted to 156 images obtained per slice each for the selective attention task and for the response inhibition task.

At the end of the functional imaging session, a high resolution, T1 weighted 3D image was acquired (SPGR, TR = 21 ms, TE = 8 ms, flip angle =  $20^\circ$ , matrix size =  $256 \times 256$ , field of view = 22 cm, slice thickness = 1 mm). These scanning parameters resulted in a  $.86 \times .86 \times 1$  mm voxel size. The acquisition of the anatomical scan took 8.6 minutes. The orientation of this 3D volume was identical to the functional slices.

**Image data analysis.** Most of the analysis of the data was performed using SPM-99 (Friston et al., 1995a, 1995b; Friston, Jezzard, & Turner, 1994). Personalized software with modules in AVS (Advanced Visual Systems, Waltham, MA) was used for visualization.

The functional images were realigned (3D) to the last functional volume in the scanning session using affine transformations. No individual runs had more than 2.0 mm movement (less than 1/2 the voxel size) from the beginning to the end of the run in the x-plane,

**Table 1** Means (and ranges) in millimeters for control and ADHD children movement in the X, Y and Z directions for the selective attention blocks with nine stimuli (Nine) and with one stimulus (One) and for the no-go and go response inhibition blocks with nine stimuli

Group	Coordinates		
	X	Y	Z
Control			
Attention Nine	.10(.05–.20)	.23(.10–.63)	.29(.08–.59)
Attention One	.10(.03–.25)	.23(.12–.69)	.30(.11–.84)
No-Go Nine	.10(.03–.24)	.33(.16–.83)	.49(.07–1.17)
Go Nine	.11(.04–.28)	.33(.15–.86)	.53(.08–1.85)
ADHD			
Attention Nine	.14(.05–.39)	.28(.04–.94)	.56(.11–1.48)
Attention One	.13(.07–.29)	.25(.04–.69)	.48(.11–1.10)
No-Go Nine	.18(.03–.47)	.49(.05–1.35)	.85(.27–1.67)
Go Nine	.14(.03–.27)	.40(.04–.72)	1.03(.25–1.90)

y-plane, or z-plane (see Table 1 for estimates of movement). There were no significant group differences in the amount of movement except for ADHD children moving more than control children on the response inhibition task in the z-plane. If the three ADHD children with the most movement were removed from the analyses, then there was no longer a significant difference between groups. For this reason, we compared activation within and between groups for the response inhibition task with and without these three subjects. All statistical analyses were conducted on these movement-corrected images.

Realigned images were segmented (gray matter, white matter, cerebrospinal fluid and scalp), and the gray-white matter information was used to co-register the structural and functional images. The co-registered images were normalized to the Montreal Neurological Institute (MNI) stereotaxic template (12 linear affine parameters for brain size and position, 8 non-linear iterations and  $2 \times 2 \times 2$  nonlinear basis functions for subtle morphological differences). The MNI template is similar to the Talairach and Tournoux (1998) stereotaxic atlas (Talairach & Tournoux, 1988) and there are algorithms to convert between coordinate spaces (Calder, Lawrence, & Young, 2001; Duncan et al., 2000). Previous studies have shown that normalization to a standard template is appropriate for children older than 8 years of age and for voxel sizes greater than about 3.5 mm (Burgund et al., 2002; Kang, Burgund, Lugar, Petersen, & Schlaggar, 2003; Muzik, Chugani, Juhász, Shen, & Chugani, 2000; Wilke, Schmithorst, & Holland, 2002).

Statistical analyses were calculated on the smoothed data (7 mm isotropic Gaussian kernel) using a delayed boxcar design with a 6-second delay from onset of block in order to account for the lag in hemodynamic response. Preprocessing of the data also included the use of a high pass filter equal to 2 cycles of the experimental and control conditions (156 seconds) in order to remove signal drift, cardiac and respiratory effects, and other low frequency artifacts.

Random effect statistics allowed generalization to the population and required a first and second level of analysis. In the first-level analysis, we calculated parameter estimate images for individual subjects

across the entire brain. For each individual, we calculated 3 contrasts: selective attention blocks with nine stimuli minus selective attention blocks with one stimulus, response inhibition no-go blocks with nine stimuli minus go blocks with nine stimuli, and selective attention blocks with nine stimuli minus go blocks with nine stimuli. Using the go blocks as the baseline for both the selective attention and response inhibition paradigms meant that the experimental and control blocks were equated in terms of visual information. In the second-level analysis, the parameter estimate images for each contrast were entered into statistical analyses. One and two-sample Z-tests were used for comparisons. Unless otherwise noted, all reported areas of activation are significant using  $p < .001$  uncorrected at the voxel level and contain a cluster size greater than or equal to 10 voxels.

## Results

### Standardized testing

Table 2 presents means on the standardized measures and the behavioral rating scales for control and ADHD children. Standardized measures for all children were within the normal range (80–130 scaled scores). There were no significant group differences for verbal or performance IQ (Wechsler, 1991), vocabulary measures (Dunn & Dunn, 1997; Woodcock, 1997), non-word reading (Woodcock, 1997), phonological awareness (Wagner et al., 1999), or mathematics achievement (Wilkinson, 1993). This suggests that the control and ADHD group were well matched on their cognitive functioning ability. Although the control children scored significantly higher than the ADHD children on reading and spelling achievement (Wilkinson, 1993), all scores were within the normal range. Most importantly, the ADHD children scored significantly higher than the control children on parental ratings of inattentiveness  $F(1, 23) = 10.93, p < .001$ , and hyperactivity-impulsivity,  $F(1, 23) = 6.68, p < .001$ .

### Behavioral performance

Table 3 presents error rates and reaction times on the selective attention task and the response inhibition task. In order to examine population differences on the selective attention task, we calculated a 2 group (control, ADHD)  $\times$  2 session (practice, test)  $\times$  2 block (nine, one) ANOVA separately on error rates and reaction time. This analysis showed that ADHD children had more errors,  $F(1, 95) = 20.27, p < .001$ , and slower reaction times,  $F(1, 95) = 21.46, p < .001$ , compared to control children. This analysis also showed that the blocks with nine stimuli elicited slower reaction times than the blocks with one stimulus,  $F(1, 95) = 64.75, p < .001$ .

In order to examine population differences on the response inhibition task, we calculated a 2 group (control, ADHD)  $\times$  2 session (practice, test)  $\times$  2 block

**Table 2** Means (*M*) and standard deviations (*SD*) for control and ADHD children on the standardized measures and the behavioral rating scales

Measure	Control		ADHD		<i>p</i> -value
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
WISC-III Verbal IQ (Wechsler, 1991)	113.6	10.0	112.4	12.6	.801
WISC-III Performance IQ (Wechsler, 1991)	101.0	12.7	109.2	16.5	.191
PPVT-III (Dunn & Dunn, 1997)	115.3	10.4	118.3	8.8	.464
WJ-III Picture Vocabulary (Woodcock, 1997)	104.7	11.8	110.7	8.1	.177
WJ-III Word Attack (Woodcock, 1997)	105.5	8.3	101.0	10.0	.245
CTOPP Phonological Awareness (Wagner et al., 1999)	97.5	12.7	98.3	11.6	.869
WRAT-3 Reading (Wilkinson, 1993)	112.1	8.7	101.3	9.6	.010
WRAT-3 Spelling (Wilkinson, 1993)	112.4	11.0	96.0	11.4	.002
WRAT-3 Math (Wilkinson, 1993)	109.8	15.9	99.2	12.5	.094
DBRS Hyperactive-Impulsive (Barkley & Murphy, 1998)	.32	.42	1.62	.57	.000
DBRS Inattentive (Barkley & Murphy, 1998)	.50	.42	2.34	.39	.000

Note: All standardized measures are standard scores with a mean of 100 and a standard deviation of 15 on the normative sample. The DBRS rating scales are on a 3-point scale. The right column indicates the *p*-value based on a *t*-test between groups.

**Table 3** Means (*M*) and standard errors (*SE*) for error rates (%) and reaction time (RT in ms) for the practice and fMRI sessions for the selective attention blocks with nine stimuli (Nine) and with one stimulus (One) and for the no-go and go response inhibition blocks with nine stimuli

Group	Practice				fMRI			
	Error rates		RT		Error rates		RT	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Control								
Attention Nine	8.6	1.7	891	32	5.7	1.3	853	39
Attention One	4.8	1.4	666	30	4.6	.8	673	34
No-Go Nine	5.8	1.2	835	38	6.4	1.1	813	32
Go Nine	5.1	1.3	509	45	2.9	1.0	492	49
ADHD								
Attention Nine	15.6	2.9	981	37	16.8	4.7	976	35
Attention One	10.8	2.7	779	35	13.9	3.2	799	37
No-Go Nine	14.4	2.6	944	36	16.0	3.4	930	46
Go Nine	7.2	2.3	628	40	12.5	5.0	644	52

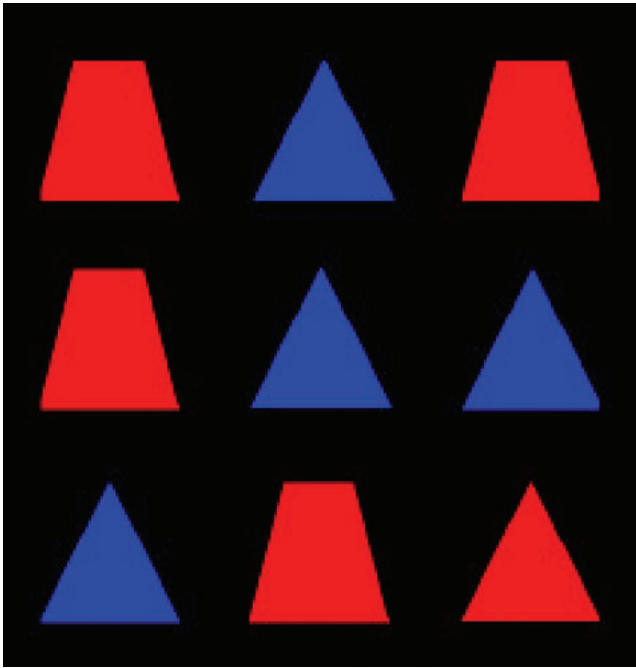
(no-go, go) ANOVA separately on error rates and reaction time. Error rates for the go blocks include only omissions (misses) because participants were supposed to press the button for every stimulus, whereas error rates for the no-go blocks include omissions as well as commissions (false alarms) because participants were asked to withhold a response when the target was present. This analysis showed that ADHD children had more errors,  $F(1, 95) = 17.41$ ,  $p < .001$ , and slower reaction times,  $F(1, 95) = 16.93$ ,  $p < .001$ , compared to control children. This analysis also showed that the no-go blocks had more errors,  $F(1, 95) = 4.09$ ,  $p < .05$ , and slower reaction times,  $F(1, 95) = 107.82$ ,  $p < .001$ , compared to the go blocks. We calculated an additional 2 group (control, ADHD)  $\times$  2 session (practice, test) ANOVA to examine group differences in commissions. Block could not be used as an independent variable in this analysis because commissions were not possible in the go blocks. This

analysis revealed that ADHD children ( $M = 10.3$ ;  $SE = 2.2$ ) showed significantly more commissions than control children ( $M = 5.3$ ;  $SE = .9$ ),  $F(1, 47) = 8.62$ ,  $p < .01$ .

The lack of significant main effects or interactions involving session ( $ps > .25$ ) for the selective attention and response inhibition tasks indicates that the environment of the scanner may not have affected the performance for either group. There were also no significant interactions between group and block for the selective attention or response inhibition task ( $ps > .35$ ). In other words, the difference between the no-go and go blocks for the response inhibition task and the differences between the nine stimuli and one stimulus for the selective attention task were similar for the control and ADHD children. This indicates that any group-by-block differences in patterns of brain activation may not be associated with performance differences because, like the behavioral analyses, our fMRI analysis examined group differences in the nine stimuli versus one stimulus blocks for selective attention and in the no-go versus go blocks for response inhibition. We also calculated a 2 group (control, ADHD)  $\times$  2 session (practice, test)  $\times$  2 block (no-go, go or nine, one)  $\times$  2 task (selective attention, response inhibition) ANOVA. This analysis revealed no significant group-by-task interactions or group-by-block-by-task interactions ( $ps > .70$ ) for either error rates or reaction times. This indicates that different group differences in activation for the selective attention and response inhibition tasks may not be accounted for by performance differences.

#### Brain activation for selective attention

Figure 2 (see Table 4 for numerical data) presents significantly greater activation for the selective attention blocks with nine stimuli compared to the blocks with one stimulus ( $p < .001$ ) for control children (red), for ADHD children (green) and for the

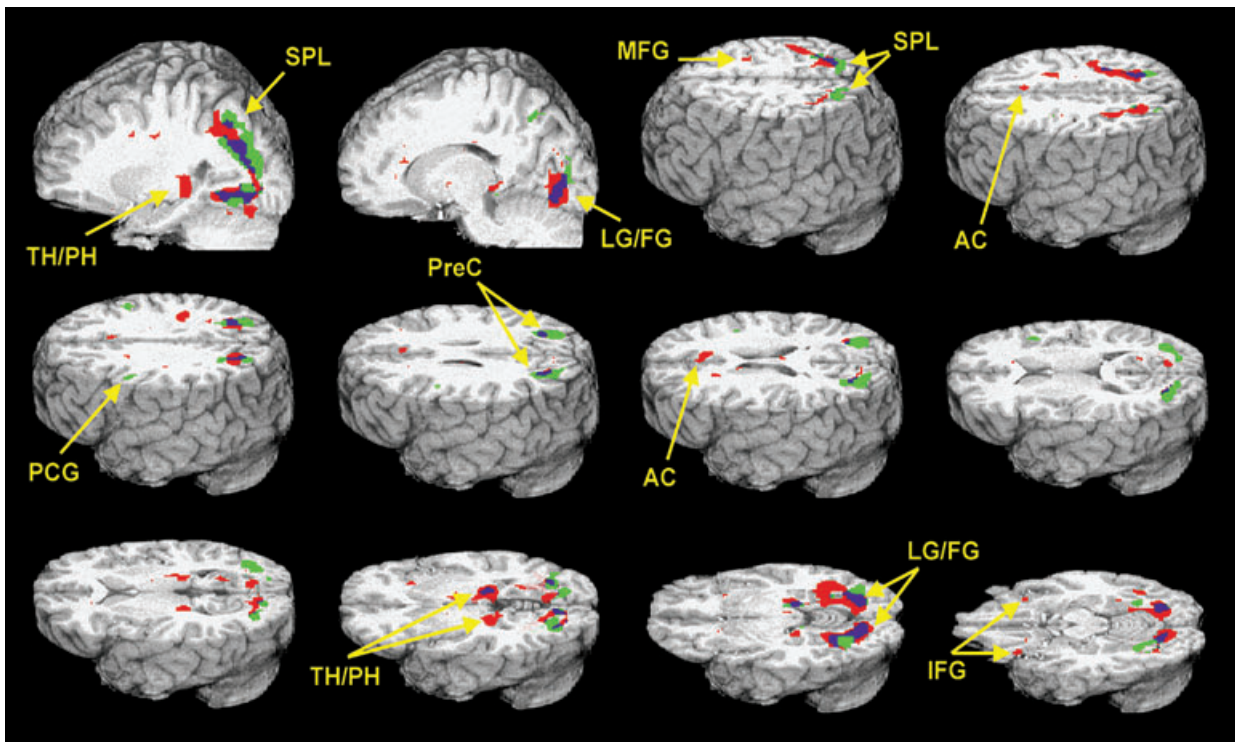


**Figure 1** An example of a trial in the selective attention and response inhibition task in which the target (red triangle) is in a field of eight distracters

overlap between control and ADHD children (purple). In general, the patterns of activation for the control and ADHD children were similar. Both groups

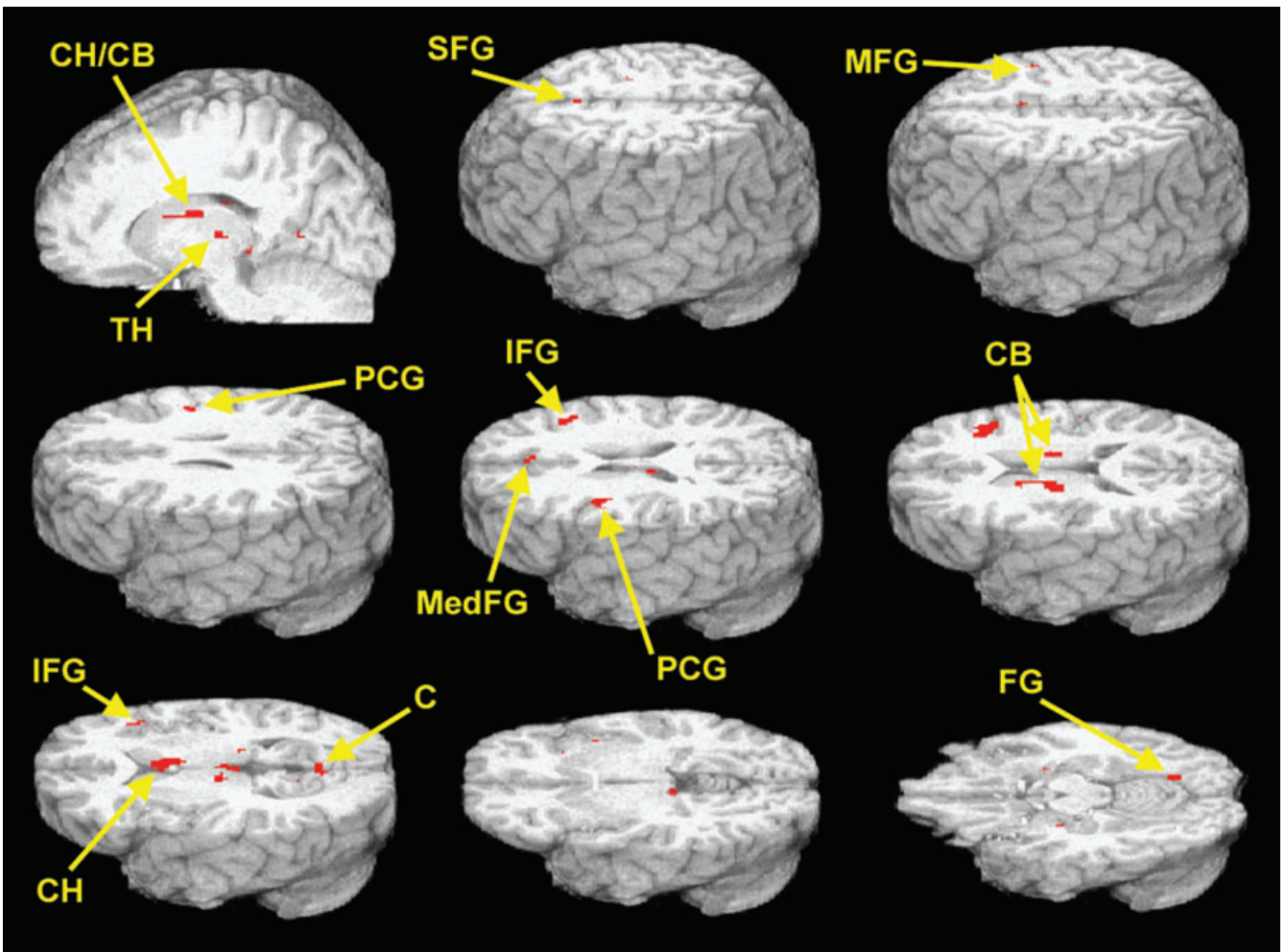
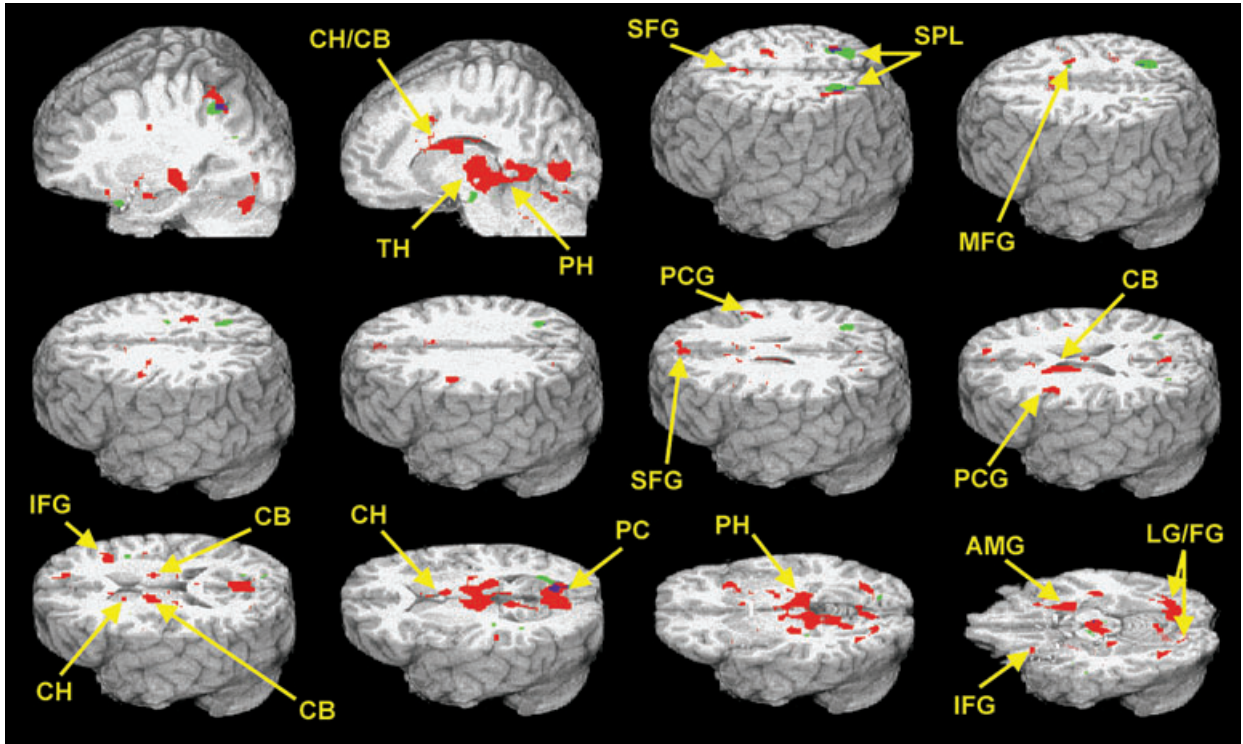
**Figure 3** Significantly greater activation for the no-go blocks compared to the go blocks of the response inhibition task. Red indicates activation for control children ( $p < .001$ ), green indicates activation for ADHD children ( $p < .05$ ) and purple indicates activation that overlaps for control and ADHD children. Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels ( $\geq 30$ ) were labeled (AMG: amygdala; CB: caudate body; CH: caudate head; IFG: inferior frontal gyrus; LG/FG: lingual and fusiform gyrus; MFG: middle frontal gyrus; PH: parahippocampus; PC: posterior cingulate; PCG: precentral gyrus; SFG: superior frontal gyrus; SPL: superior parietal lobule; TH: thalamus)

**Figure 4** Significantly greater activation (red) for control than ADHD children in the no-go blocks compared to the go blocks of the response inhibition task ( $p < .001$ ). Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels ( $> 10$ ) were labeled (CB: caudate body; CH: caudate head; C: cuneus; IFG: inferior frontal gyrus; FG: fusiform gyrus; MedFG: medial frontal gyrus; MFG: middle frontal gyrus; PCG: precentral gyrus; SFG: superior frontal gyrus; TH: thalamus)



**Figure 2** Significantly greater activation for the selective attention blocks with nine stimuli compared to the blocks with one stimulus ( $p < .001$ ). Red indicates activation for control children, green indicates activation for ADHD children and purple indicates activation that overlaps for control and ADHD children. Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels ( $\geq 30$ ) were labeled (AC: anterior cingulate; IFG: inferior frontal gyrus; LG/FG: lingual to fusiform gyrus; MFG: middle frontal gyrus; PreC: precuneus; PCG: precentral gyrus; SPL: superior parietal lobule; TH/PH: thalamus and parahippocampus)





exhibited a large amount of bilateral activation in precuneus to superior parietal lobule and from lingual to fusiform gyrus. Both groups also showed activation in the hippocampal area and thalamus, but this was bilateral for control children and confined to the right hemisphere for ADHD children. Both groups also showed activation in the inferior frontal gyrus, but this activation was bilateral for control children and confined to the right hemisphere for ADHD children. Both groups also showed activation in the precentral gyrus, but this activation was bilateral for ADHD children and confined to the left hemisphere for control children. The major difference in the control versus ADHD activation maps was that only the control children showed areas of activation in the right middle frontal gyrus and in the left and right anterior cingulate. However, the data presented in Figure 2 and Table 4 does not involve a direct statistical comparison between control and ADHD children. A direct statistical comparison of the selective attention task (nine stimuli versus one stimulus) revealed no significant group differences (ADHD > control or control > ADHD) in any region. Statistical comparisons are necessary to determine reliable differences between the groups. For example, control children may show activation in an area because it is just over threshold, whereas ADHD children may show no activation in this area because it is just under threshold. In this case, a direct statistical test may yield no significant group differences.

### *Brain activation for response inhibition*

Figure 3 (see Table 5 for numerical data) presents significantly greater activation in the no-go blocks compared to the go blocks of the response inhibition task for control children (red), for ADHD children (green) and for the overlap between control and ADHD children (purple). The control children showed several clusters of activation ( $p < .001$ ) including bilateral superior parietal lobule, bilateral superior frontal gyrus, right middle frontal gyrus, bilateral inferior frontal and precentral gyri, left caudate body, bilateral cuneus to the hippocampal region, and bilateral amygdala. ADHD children did not show any significant clusters of activation at the  $p < .001$ , so the data presented is at the  $p < .05$  level of significance. At this significance level, ADHD children showed clusters of activation in bilateral superior parietal lobule, right precuneus, bilateral posterior cingulate/parahippocampus and brain stem. We also calculated these analyses without the 3 ADHD children who showed the most movement and these 4 regions were still significantly activated at  $p < .05$ , but with a fewer number of voxels.

Figure 4 (see Table 6 top for numerical data) shows significantly greater activation (red) for the control children compared to the ADHD children in the no-go blocks compared to the go blocks of the response inhibition task. As reviewed above, a direct

comparison between control and ADHD children is necessary to make conclusive statements about group differences. A direct statistical comparison revealed that control children exhibited significantly greater activation than ADHD children in several brain regions. The largest clusters included bilateral precentral gyrus, bilateral caudate body, right caudate head, right inferior frontal gyrus and bilateral thalamus. A direct comparison between the ADHD and control children did not show significantly greater brain activation in any brain region for the ADHD children for the whole data set and for the data set without the 3 ADHD subjects who showed the most movement in the  $z$  direction. Although statistical power is reduced due to fewer subjects, after removing these 3 subjects there was no longer a statistical difference in the amount of movement between the control and ADHD children.

### *Brain activation for selective attention revisited*

To further examine group differences in selective attention, we compared the selective attention blocks with nine stimuli to the go blocks of the response inhibition task with nine stimuli. The rationale for this was that both blocks would be equated for stimulus characteristics, and therefore, this contrast may be more sensitive to group differences in selective attention. The results for the control and ADHD separately in this analysis were similar to the results reported in Figure 2 and Table 4 that compared selective attention blocks with nine stimuli to the blocks with one stimulus, so we do not present the within-group analysis here. Figure 5 (see Table 6 bottom for numerical data) presents significantly greater activation for control children than for ADHD children on selective attention blocks with nine stimuli to the go blocks of the response inhibition task with nine stimuli. Although the clusters were small, this analysis revealed significantly greater activation for control children in right superior parietal lobule, right cuneus to middle temporal gyrus and left fusiform gyrus. ADHD children did not exhibit significantly greater activation than control children for this comparison in any region.

## **Discussion**

Both control and ADHD children showed activation in our regions of interest for the visual selective attention task that required visual search of a conjunction of features. Our finding of activation in the superior parietal lobule for both groups is generally consistent with past neuroimaging studies with adults that have examined visual selective attention and conjunction search (Corbetta et al., 1995; Donner et al., 2000; Gitelman et al., 1999; Kim et al., 1999; Nobre et al., 2000). We also measured brain activation during a task that required the inhibition of a response during no-go blocks that was

**Table 4** Significantly greater activation for control or for ADHD children in the selective attention blocks with nine stimuli compared to the blocks with one stimulus

Group	Location Area	BA	Significance		Coordinate		
			z-test	voxels	X	Y	Z
Control	Superior Parietal Lobule/Precuneus/ Lingual Gyrus/Fusiform Gyrus	7/19/18/37	5.36	1861	27	-57	48
	Precentral Gyrus	6	4.28	38	-33	-18	30
	Inferior Frontal Gyrus	47	3.92	32	30	27	-3
		47	3.96	30	-30	24	-18
	Thalamus/Parahippocampus	*/27	5.31	200	24	-30	-3
		*/27	5.13	102	-21	-30	0
	Middle Frontal Gyrus	6	4.14	64	27	0	45
	Anterior Cingulate	32	4.68	26	9	21	36
		32	4.52	39	12	33	21
		32	4.38	16	-18	9	36
		32	3.94	25	-12	30	15
	Posterior Cingulate	31	4.25	20	24	-60	15
	Medial Globus Pallidus	*	3.68	19	12	-6	-3
	ADHD	Superior Parietal Lobule/Precuneus	19/7	5.12	838	27	-60
Lingual Gyrus/Fusiform Gyrus		18/19/37	5.76	759	-27	-81	12
Precentral Gyrus		6	3.68	15	48	9	33
		6	3.88	34	-45	6	27
Inferior Frontal Gyrus		44	3.89	17	51	15	9
Thalamus/Parahippocampus		27	4.5	56	21	-30	-3

Note: BA: Brodmann's area of peak activation as determined by z-test ( $p < .001$  uncorrected at the voxel level). Voxels: number of voxels in cluster including this peak, only clusters 10 or greater are presented. Coordinates: -X left hemisphere, +X right hemisphere, -Y behind anterior commissure, +Y in front of anterior commissure, -Z below anterior-posterior commissure plane, +Z above anterior-posterior commissure plane. Regions activated in both groups (control and ADHD) are listed first. Some of the regions contained multiple clusters - right hemisphere clusters are always listed first.

trained during go blocks. Only control children produced activation in our fronto-striatal regions of interest including the caudate head/body and the inferior, middle, superior and medial frontal gyri. Our results for the control children are consistent with developmental response inhibition studies that have reported fronto-striatal activation during go/no-go tasks (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Casey et al., 1997b; Durston et al., 2002), stop tasks (Rubia et al., 2000a), delay tasks (Rubia et al., 2000a) and anti-saccade tasks (Luna et al., 2001).

Our study showed small differences in activation between the ADHD and controls during the selective attention task. These group differences for our regions of interest only emerged when comparing the selective attention blocks with nine stimuli to the go blocks with nine stimuli. Note that the go blocks required minimal involvement of attentional resources since a quick response was required at stimulus onset regardless of stimulus configuration; thus, using go blocks as a baseline should provide maximal sensitivity for demonstrating attentional effects. Our finding of significantly lower intensity of activation for ADHD children than for control children in the superior parietal lobule (10 voxels) is consistent with structural studies that show ADHD children have smaller volume (Castellanos et al., 2002; Filipek et al., 1997) and lower metabolism in

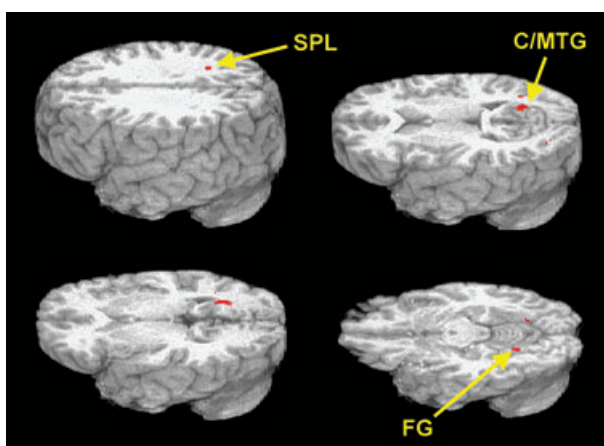
the parietal region (Ernst et al., 1997). Although ERP studies have limited spatial resolution, our finding of lower intensity of activation for ADHD children in the parietal region is also consistent with evoked potential studies (Brandeis et al., 1998; Karayanidis et al., 2000; Robaey et al., 1992; van Leeuwen et al., 1998). The hypoactivity in the superior parietal lobule for the ADHD children in our study could reflect their lack of engagement of this system for representing extrapersonal space. It is essential to have a complete and accurate representation of the visual array in order to efficiently search this array for the target in a field of distracters.

The response inhibition task also required visual search in order to detect the presence or absence of a target in a field of distracters, so not surprisingly the no-go task produced activation in the selective attention network. Both the control ( $p < .001$ ) and ADHD children ( $p < .05$ ) showed activation in bilateral superior parietal lobule and in predominantly right middle frontal gyrus. In contrast to the small group differences in selective attention, however, our study found large group differences between ADHD and control children for the response inhibition task. ADHD children showed significantly lower intensity of activation than control children in our regions of interest including the right inferior frontal gyrus (68 voxels) and bilateral caudate nucleus (155 voxels). The hypoactivity for

**Table 5** Significantly greater activation for control or for ADHD children in the no-go blocks compared to the go blocks of the response inhibition task

Group	Location Area	BA	Significance		Coordinate		
			z-test	voxels	X	Y	Z
Control	Superior Frontal Gyrus	8	3.83	89	3	18	54
		10	5.02	106	15	57	21
	Middle Frontal Gyrus	6	3.90	77	27	0	42
	Inferior Frontal Gyrus	44	4.60	40	42	24	15
	Inferior Frontal Gyrus	47	3.68	49	-30	27	-12
	Precentral Gyrus	6	3.79	51	48	-3	27
		6	4.14	106	-42	0	33
	Caudate Head/Body	*	4.21	212	-12	-3	18
	Insula	13	3.76	22	-42	-30	0
	Posterior Cingulate	31	3.70	10	-24	-78	12
	Parahippocampus/Posterior Cingulate/Lingual Gyrus/Fusiform Gyrus	35/27/29/ 18/19/37	5.34	2296	-30	-24	-9
	Superior Parietal Lobule	7	3.73	45	30	-54	57
		7	3.85	64	33	-33	36
	Amygdala	7	4.20	104	-30	-45	57
		*	4.50	44	45	-12	-18
		*	3.57	40	-21	-3	-18
ADHD	Insula	13	2.07	16	42	9	15
		7	2.60 <sup>a</sup>	82	-24	-51	51
	Posterior Cingulate/ Parahippocampus	30/36	2.73 <sup>a</sup>	117	30	-60	3
	Superior Parietal Lobule/ Precuneus	7	2.75 <sup>a</sup>	230	21	-60	48
	Brainstem	*	2.76 <sup>a</sup>	98	-3	-15	-21
	Superior Temporal Gyrus	42	2.38	16	-33	-30	6
	Middle Temporal Gyrus	21	2.59	14	-39	-48	3
	Inferior Temporal Gyrus	20	2.58	17	48	-9	-24

Note: See Table 4 note. Brain areas in our regions of interest (fronto-striatal) are listed first and then areas outside of these regions that are activated in both groups are listed next. For the ADHD only,  $p < .05$  uncorrected at the voxel level. <sup>a</sup>indicates that this region was also significant at the  $p < .05$  level when excluding the 3 ADHD subjects with the most movement.



**Figure 5** Significantly greater activation (red) for control than ADHD children in the selective attention blocks with nine stimuli compared to the go blocks of the response inhibition task with nine stimuli ( $p < .001$ ). Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels ( $\geq 10$ ) were labeled (C/MTG: cuneus and middle temporal gyrus; FG: fusiform gyrus; SPL: superior parietal lobule)

ADHD children in fronto-striatal regions is consistent with structural neuroimaging research that shows ADHD subjects have smaller frontal and basal ganglia volumes (Aylward et al., 1996; Casey et al., 1997a; Castellanos et al., 1996, 2002; Filippek et al., 1997; Hynd et al., 1993; Yeo et al., 2003). This hypoactivity is also consistent with functional neuroimaging research that shows less activation in ADHD subjects than controls in frontal and basal ganglia regions (Amen & Carmichael, 1997; Bush et al., 1999; Ernst et al., 1997, 1998a; Jin et al., 2001; Rubia et al., 1999, 2001; Zametkin et al., 1990).

As reviewed in the introduction, Casey et al. (2001) have proposed that the prefrontal region is involved in interference control from competing representations and the basal ganglia is involved in the inhibition of inappropriate behaviors (Casey et al., 2001). Our results suggest that ADHD children have deficits in both components of the fronto-striatal network. These children are not able to effectively engage this network to maintain appropriate behaviors or inhibit inappropriate behaviors.

**Table 6** Significantly greater activation for control than for the ADHD children in the no-go compared to the go blocks of the response inhibition task and in the selective attention blocks with nine stimuli compared to the go blocks of the response inhibition task with nine stimuli

Group	Location Area	BA	Significance		Coordinate		
			z-test	voxels	X	Y	Z
No-go	Superior Frontal Gyrus	8	3.52	13	0	15	54
	Middle Frontal Gyrus	6	3.4	19	24	-9	48
		6	3.68	16	45	3	45
		11	3.59	10	-21	30	-12
	Inferior Frontal Gyrus	44	4.22	68	42	27	15
	Medial Frontal Gyrus	10	4.15	17	21	51	9
	Anterior Cingulate	32	3.32	10	9	42	6
	Precentral Gyrus	6	4.01	31	45	-6	24
		6	4.2	31	-36	9	21
	Caudate Head	*	4.17	53	6	12	3
	Caudate Body	*	3.73	46	12	-9	18
		*	4.19	56	-12	-3	18
	Globus Pallidus	*	3.49	10	-9	-33	-6
	Amygdala	*	3.94	13	30	-3	-15
	Cuneus	30	3.93	28	-3	-72	3
	Fusiform Gyrus	19/37	3.49	23	27	-63	-21
	Thalamus	*	3.5	38	3	-24	3
SEL ATT	Cuneus/Middle Temporal Gyrus	30/37	4.01	81	39	-57	3
	Fusiform Gyrus	19/37	3.67	10	-24	-57	-12
	Superior Parietal Lobule	7	3.9	10	27	-51	36

Note: See Table 4 note.

Less activation in this network could result for a variety of reasons. As reviewed above, quite a bit of evidence suggests that the fronto-striatal networks are underdeveloped in ADHD subjects by showing decreased volumes in these regions. However, our findings could also be explained by differences in functional or effective connectivity (McIntosh, Nyberg, Bookstein, & Tulving, 1997; Pugh et al., 2000).

Although Vaidya et al. (1998) did not investigate selective attention, they used a stimulus-controlled go/no-go task similar to ours and also found less activation in ADHD subjects compared to controls in the basal ganglia (Vaidya et al., 1998). Stimulus-controlled refers to paradigms that have an equal number of items in the go and no-go blocks. However, Vaidya et al. (1998) also reported that ADHD children showed more activation than controls in the caudate nucleus during a response-controlled go/no-go task. Response-controlled paradigms equate the number of motor responses made in the go and no-go blocks, and therefore there are 50% fewer stimuli in the go than in the no-go blocks. The stimulus- and response-controlled tasks may have created different inhibitory demands. There were 50% fewer trials in go blocks for the response-controlled task, and therefore, the establishment of a pre-potent response requiring inhibition may have been stronger in the stimulus-controlled task. The greater inhibitory demands of the stimuli-controlled paradigms may be more sensitive to the hypoactivity of ADHD children.

The results for our behavioral data suggest that group differences in performance may not account for brain activation differences between the control and ADHD children. The behavioral data showed that ADHD children perform more poorly (higher reaction times and lower accuracy) on all blocks. In other words, the difference between the no-go and go blocks for the response inhibition task and the difference between the nine stimuli and one stimulus blocks for the selective attention task were statistically the same for the control and ADHD children. Furthermore, the group differences between these blocks in behavioral performance were similar for the selective attention and response inhibition task. In contrast to the behavioral data, when comparing no-go versus go blocks, there was widespread hypoactivity for the ADHD children, but when comparing nine stimulus blocks to one stimulus blocks, there were no significant group differences in activation. The mismatch between the performance and activation results could suggest that brain differences are not related to any meaningful performance difference between groups. However, future research should use parametric manipulations and event-related designs to more clearly specify the association between behavioral performance and brain activation in these two groups. For example, using an event-related design, Durston et al. (2002, 2003) have varied the number of go trials preceding no-go trials in order to parametrically increase the inhibitory demands (Durston et al., 2002, 2003). In our study, comparison of accuracy and reaction time

across blocks or tasks is also difficult to interpret because the measures in these comparisons differ. For example, because ADHD children made more errors than control children and the types of errors in the selective attention task (omissions and commissions) were not precisely of the same nature as the errors in the response inhibition task (only omissions for the go blocks, both omissions and commissions for the no-go blocks), a lack of interaction does not preclude the possibility that group differences in brain activation are due to the differences in the type of error produced more frequently by ADHD children in a particular block type. Similarly, comparing reaction time across the selective attention task and the response inhibition task is not ideal because we do not have a measure of the amount of time required for response inhibition in the no-go blocks. Reaction time for the no-go blocks instead reflects the amount of time required to determine that the target is absent before making a response.

The DSM-IV (American Psychiatric Association, 1994) now makes the distinction between Predominately Hyperactive-Impulsive (ADHD/H), Predominately Inattentive (ADHD/I), and Combined Type (ADHD/C). Milich, Balentine, and Lynam (2001) have argued that ADHD/C is a distinct and unrelated disorder from ADHD/I (Milich et al., 2001). The results from behavioral studies using carefully designed experimental tasks suggest that inhibition deficits in ADHD/C subjects may be associated with executive functioning (Gansler et al., 1998; Houghton et al., 1999; Klorman et al., 1999; Lockwood, Marcotte, & Stern, 2001; Nigg, Butler, Huang-Pollock, & Henderson, 2002; Trommer, Hoepfner, Lorber, & Armstrong, 1988), whereas attention deficits in ADHD/I subjects may be associated with processing speed (Hynd et al., 1991). ERP and electroencephalography studies have reported some differences between the ADHD subtypes, but these studies cannot pinpoint the location due to limited spatial resolution (Clarke, Barry, McCarthy, & Selikowitz, 2001; Defrance, Smith, Schweitzer, Ginsberg, & Sands, 1996; Johnstone, Barry, & Anderson, 2001). Hesslinger et al. (2001) recently showed that ADHD/C adults showed less N-acetylaspartate concentration than ADHD/I adults in left dorso-lateral prefrontal cortex and that there was no difference between these groups in left striatum (Hesslinger, 2001). Our study included mainly ADHD/C children, so we could not reliably examine subtypes. All ADHD children in our study had 6 or more symptoms of inattention and 8 of 12 ADHD children had 6 or more symptoms on the hyperactive-impulsive scale. Only two children in our study had two or fewer symptoms of hyperactivity-impulsivity, so only these two children were at levels of hyperactivity-impulsivity comparable to our control children. Because our population included mostly children with hyperactive-impulsive symptoms, our results

cannot be generalized to the entire ADHD population. Perhaps a population of children with predominantly inattentive symptoms would reveal brain activation differences in the selective attention network during our visual search task.

Another limitation of our study was that we did not have enough subjects to examine sex differences in the neural profiles of ADHD. Two recent meta-analyses of the literature have shown that boys tend to have more hyperactivity and externalizing problems, whereas girls have greater intellectual impairments (Gaub & Carlson, 1997; Gershon, 2002). These behavioral differences seem to have an underlying neurological component. Animal studies have shown that dopamine transmitters rapidly increase during development and then are pruned to a greater extent in males than females (Andersen & Teicher, 2000), and human neuroimaging studies have also suggested some difference between males and females (Ernst et al., 1994; Ernst, Zametkin, Phillips, & Cohen, 1998b; Yeo et al., 2003).

## Conclusion

This study reported small group differences between control and ADHD children in brain activation during selective attention as measured by a visual search task. This small difference may indicate little involvement of the superior parietal lobule and lateral premotor network in our ADHD population. In contrast, there was widespread hypoactivity in the ADHD children during response inhibition as measured by a go/no-go task. The larger population difference for the go/no-go task in the fronto-striatal network is consistent with response inhibition being the primary deficit in ADHD as suggested by previous genetic, brain imaging and behavioral research. More neuroimaging research directly comparing different response inhibition tasks with selective attention tasks is needed in order to determine whether our results are task specific or generalizable.

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## Correspondence to

James R. Booth, Department of Communication Sciences and Disorders, Northwestern University, 2240 Campus Drive, Evanston, Illinois, 60208, USA; Tel: (847) 491-2519; Fax: (847) 491-4975; Email: j-booth@northwestern.edu

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## Clinical Research

# Components of Attention in Children with Complex Partial Seizures With and Without ADHD

Margaret Semrud-Clikeman and \*Beverly Wical

*Department of Educational Psychology, University of Texas, Austin, Texas; and \*Department of Neurology, University of Minnesota Medical School, Minneapolis, Minnesota, U.S.A.*

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**Summary:** *Purpose:* To evaluate attentional difficulties in children with complex partial seizures, we reviewed the records of 12 children with complex partial seizures with attention deficient hyperactivity disorder (CPS/ADHD); 21 children with CPS without ADHD (CPS); 22 children with ADHD; and 15 control children.

*Methods:* Each child completed a computerized performance test (CPT), which evaluated sustained attention, inhibition of response, response time, and consistency of response. The ADHD groups also completed the CPT after a dose of methylphenidate.

*Results:* The results found poorest performance on the CPT

by the CPS/ADHD group. Particular difficulty in attention was found for children with epilepsy regardless of the ADHD diagnosis. When methylphenidate was administered to the ADHD groups, both groups improved in performance on the CPT.

*Conclusions:* Epilepsy may predispose children to attention problems that can significantly interfere with learning. Similar improvement for children with CPS/ADHD was found with methylphenidate compared with baseline as for children with ADHD but without CPS. **Key Words:** Epilepsy—ADHD—Attention—Children—Partial—complex.

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Attention deficit hyperactivity disorder (ADHD) includes symptoms of poor attention to task, impulsive behavior, and motoric overactivity. It is considered a heterogeneous disorder thought to affect between 3 and 5% of the school population (1). Epilepsy also is a heterogeneous disorder thought to affect between 2 and 4% of the school population (2). A higher than expected incidence of ADHD has been found in children with epilepsy, estimated at 35–40% (3). Many believe that when more than one disorder occurs in a child, that child shows a more severe form of disability (4).

Attentional difficulties have been found to be closely associated with educational problems, and ~40–50% of children with attentional problems and epilepsy experience difficulty learning in school (5,6). Impaired performance in children with epilepsy has been found on tests of reading, written language, and spelling (7–9), as well as on teacher reports of difficulties in attention, concentration, and information processing (10).

Attention appears to contain multiple aspects that interact with motor, cognitive, and social development. Disruption of any component may compromise the efficiency of the total system. A breakdown in the sequencing of information due to attentional problems would negatively affect classroom tasks, which often require bit-by-bit information processing as well as reconstruction of information into a whole. Recent studies supported a hypothesis of a generalized self-regulatory deficit that affects information processing, inhibition of responses, arousal/alertness, planning, and ability to self-monitor (11). Because longer reaction times for children with ADHD have been found (12–14), measures of reaction time and variability of reaction time across trials on continuous performance tests (CPTs) may be sensitive to sustained attention difficulties in children with ADHD.

Currently studies that directly evaluated attention in children with epilepsy both with and without ADHD are lacking. Not only is there a need for further understanding of this conjoint diagnosis, but there is also a need to evaluate the shared underpinnings of these disorders to arrive at a more economic and efficacious treatment model. It may well be that treatment will differ in chil-

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Address correspondence and reprint requests to Dr. M. Semrud-Clikeman at Department of Educational Psychology, SZB 504, University of Texas, Austin, TX 78413, U.S.A.

dren with epilepsy and ADHD from usual treatments for children with epilepsy without ADHD and children with a sole diagnosis of ADHD.

Several questions arise as to the presentation of ADHD in children with epilepsy. Previous studies have used teacher and parent reports of the child's behavior without directly assessing attentional skills. Children with epilepsy have been reported to experience difficulty with attention, impulsivity, and activity level, symptoms commonly associated with a diagnosis of ADHD.

There are conflicting reports as to the postulated attentional deficits found in the subtypes of epilepsy. Attentional difficulties have been reported in children with absence seizures, partial complex seizures (CPS), and tonic-clonic generalized seizures (3,15). Hempel et al. (3) found that children with various types of epilepsy showed a higher level of impulsive and overactive behavior. A study evaluating the attention and memory skills in children with epilepsy, but without documented learning or behavioral difficulties, found subtle attentional problems with memory skills falling in the normal range (16). In contrast, Bennet-Levy and Stores (10) found that children with epilepsy did not differ in terms of difficulty in concentration and mental-processing speed from typically developing children. However, Bennet-Levy and Stores (10) did not evaluate different subtypes of epilepsy to determine whether there were variations between subtypes.

The attentional ability of children with localization-related epilepsy has been poorly studied. This study evaluated attention in children with CPS with and without ADHD to determine whether these groups differ in degree of attentional problems. These results were compared with those found in children with ADHD but without epilepsy. Given previous research findings that more than one diagnosis for a child leads to a more severe disorder (4), it was hypothesized that children with CPS without ADHD (CPS) would perform better on measures of attention, followed by those with ADHD; those with CPS and ADHD (CPS/ADHD) were hypothesized to perform the most poorly on a computerized measures of attention. In addition, it was hypothesized that administration of methylphenidate would normalize the results of the CPT for the two ADHD groups.

## METHODS

Our data were obtained through review of medical records from a tertiary care medical center in the mid-west United States serving five surrounding states. All children 7–16 years of age with CPS with and without ADHD, those with ADHD and no epilepsy, and those who had no diagnosis were included. Records with the appropriate diagnoses were reviewed by both of us.

All patients selected were between the ages of 7 and

16, had verbal and/or performance IQs >70, as measured by the Wechsler Intelligence Scale-Revised, and did not have a progressive neurologic disease or any co-occurring neuropsychological/psychiatric disorders (i.e., learning disabilities, anxiety disorder). All patients with CPSs had had two unprovoked seizures, had blood serum levels of antiepileptic drug (AED) within therapeutic ranges, had well-controlled seizures, were not taking phenobarbital (PB), and were taking one AED.

Classification of seizure type was accomplished using EEG and clinical judgment by a pediatric epileptologist. All patients with ADHD met DSM IIR (17) criteria for ADHD, and their symptoms occurred in two or more settings with onset before age 7, as determined by a clinical interview adapted from the Kiddie SADS (18). This semistructured interview has been well documented for its ability to provide diagnoses based on parent and child input. In addition to the Kiddie SADS (18), each child's teacher completed a form adapted from the Conner's Rating Scale (with permission, 19). Each child selected for study scored at or above the recommended cutpoint of 15 raw score points (T score of 70) or greater on the hyperactivity index. The children with ADHD had all shown a favorable response to methylphenidate for  $\geq 6$  months, as measured by both parent and teacher report during a follow-up visit with the neurologist and neuropsychologist.

All patients with ADHD without epilepsy had no history of a seizure disorder, head injury, or family history of epilepsy. A control group with no psychiatric or neurologic disorders also was obtained. This group contained no subjects with a family history of seizure or attention-deficit disorders, had no history of neurologic or neurodevelopmental disorder, and were free from a psychiatric disorder.

With these criteria, the following groups emerged: 21 children with CPS, 12 children with CPS/ADHD, 22 children with ADHD, and 15 control children. From the original sample of 56 children with CPS, 31 children were eliminated because of mental retardation, progressive neurologic disorder, or uncontrolled/unspecified seizures. From the original sample of 64 children with ADHD, 42 were excluded for co-occurring diagnoses (i.e., mental retardation, learning disability) or missing data. There was no difference in chronologic age among the groups ( $p = 0.24$ ).

All children included in the study completed the Wechsler Intelligence Scale for Children-Revised (WISC-R) and verbal, performance, and full-scale IQs (FSIQs) were available for analysis. A 3 (Verbal, Performance, Full-scale IQ)  $\times$  4 (Group) repeated-measures analysis of variance (ANOVA) indicated a significant group effect for intelligence [ $F(3, 66) = 7.78, p = 0.0002$ ]. Post hoc comparisons indicated that the clinical groups significantly differed from the control group on

each intelligence variable but did not differ from each other on any intelligence variable. The Conners Rating Scales were completed by the child's teacher, and a significant group effect was found as was expected [ $F(3, 81) = 100.1, p < 0.0001$ ]. All ADHD groups differed significantly from the CPS and control children ( $p < 0.0001$ ). Bonferroni/Dunn post hoc comparisons found that the CP group scored significantly higher than the control group ( $p = 0.007$ ). Table 1 provides this information.

The Test of Variables of Attention (TOVA, 20) was administered to each child. The TOVA is a computer-administered, visual continuous performance test, which provides four measures of attention: the ability to sustain attention (omission), the ability to inhibit response (commission), reaction time (RT), and consistency of response (variability). The TOVA presents a small yellow box on a black screen over a 22-min period. When the box is at the top of the screen, the participant is instructed to push a button. When the box is at the bottom of the screen, the button is not to be pushed. The TOVA has not been found to show a practice effect. Greenberg and Waldman (21) found no significant difference between 33 normal controls and 40 ADHD children when the TOVA was readministered 3 months after the first administration. The TOVA was administered to the ADHD groups twice: once without methylphenidate, and a second time with methylphenidate. The average amount of time between administrations of the TOVA for both groups was 6.3 months, with a median of 5 months.

Data were analyzed by using the STATVIEW program by repeated-measures ANOVA to control for type I error. Significance level was set at  $\alpha = 0.05$ . Post

hoc comparisons were accomplished through the use of Fisher's Protected LSD.

## RESULTS

A 3 (group)  $\times$  4 (Omission, Commission, Reaction time, Variability) repeated-measure ANOVA revealed a significant main effect for the TOVA when no stimulant medication was administered [ $F(3, 82) = 6.906, p = 0.0003$ ]. Post hoc assessment indicated that significantly poorer performance was present for the CPS/ADHD on all TOVA indices ( $\leq p = 0.01$ ). The CPS and ADHD groups performed significantly more poorly than the control group on all but the commission measure ( $\leq p = 0.03$ ). The CPS/ADHD performed more poorly than the ADHD on all TOVA indices except RT. The CPS and ADHD groups did not differ from each other on any TOVA variable nor did the CPS and CPS/ADHD groups. Figure 1 illustrates these differences.

To determine whether the group IQ differences could predict performance on the TOVA, correlations were obtained. The correlations between the TOVA indices and FSIQ were nonsignificant (omissions,  $p = 0.09$ ; commissions,  $p = 0.86$ ; RT,  $p = 0.28$ ; and variability,  $p = 0.396$ ). Moreover, regression analyses indicated that FSIQ accounted for 15% of the variance for omissions, 1% for commission, 9% for reaction time, and 10% for variability. To determine whether the groups differed in the amount of variance explained on TOVA performance by FSIQ, a regression analysis was conducted for each group. The  $r^2$  for the CPS group was 0.02; for the CPS/ADHD group, 0.05; for the ADHD group, 0.08; and for the controls, -0.08. These variances are relatively insignificant, particularly for the two CPS groups.

TABLE 1. Demographic information for four groups of children

	CPS (n = 21)	CPS/ADHD (n = 12)	ADHD (n = 22)	Control (n = 15)
Chronologic age	11.9 $\pm$ 3.7	9.9 $\pm$ 3.0	10.2 $\pm$ 3.2	10.3 $\pm$ 3.1
Males/females	13/8	10/2	14/8	9/6
Conners: Hyper. Index	60.8 $\pm$ 5.7	77.3 $\pm$ 5.7	75.1 $\pm$ 3.6	56.1 $\pm$ 3.96
Full-scale IQ	86.4 + 13.8	84.4 + 10.4	92.1 + 13.7	104.8 + 11.3 <sup>a</sup>
Verbal IQ	90.8 + 13.1	80.8 + 12.6	91.5 + 11.2	104.1 + 11.9 <sup>a</sup>
Performance IQ	83.9 + 15.9	88.9 + 15.2	94.5 + 17.9	103.7 + 3.4 <sup>a</sup>
Seizure Onset <3 years of age	10	7	0	0
Abnormal MRI	1	0	NA	NA
Medication				
Carbamazepine (Tegretol)	18	10	0	0
Valproate (Depakene)	1	2	0	0
Ethosuximide (Zarontin)	1	0	0	0
Lamotrigine (Lamictal)	1	0	0	0
Methylphenidate	0	12	22	0

CPS, complex partial seizures; ADHD, attention deficient hyperactivity disorder.

<sup>a</sup> Significant at 0.05.

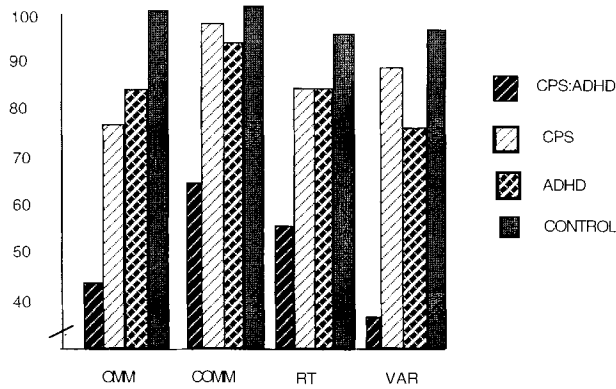


FIG. 1. TOVA without methylphenidate.

At an appointment scheduled  $\geq 1$  months later, methylphenidate was administered to the two ADHD groups, and the TOVA was readministered 90 min after the medication dose. A 2 (Group)  $\times$  4 (Omission, Commission, Reaction time, Variability) repeated-measures ANOVA produced a significant main effect [ $F(1, 32) = 5.98, p = 0.02$ ]. Figure 2 illustrates this finding. The CPS/ADHD group differed significantly from the ADHD group on the dimensions of omission ( $p = 0.0042$ ) but not on commission ( $p = 0.15$ ), RT ( $p = 0.14$ ), or variability ( $p = 0.17$ ).

## DISCUSSION

This study evaluated the relation between CPS and the attentional components measured by TOVA. The clinical groups significantly differed from the control group on the intelligence indices of the WISC-R. When the FSIQ, verbal IQ, and performance IQ were compared with the TOVA variables of omission, commission, RT, and variability, no significant correlations emerged. Moreover, regression analyses indicated that IQ explained very little of the variance between the two measures, as did group variances. In addition, the clinical groups did not significantly differ from each other on any intelligence measure and yet differed significantly from each other on the measure of attention. The finding of limited relations between intelligence measures and a continuous performance test of attention are similar to those of Seidel and Joschko (22) and Greenberg and Waldman (21).

Our first hypothesis was partially confirmed. The omission (not pushing the button when the target was present) and variability (consistency of response) components were the only TOVA components that discriminated between the clinical groups and the control group. On both variables, the CPS/ADHD group performed the poorest of the clinical groups, with no difference present between the CPS and ADHD groups. On the commission component, only the CPS/ADHD group differed significantly from the control group as well as the ADHD group. The RT component differentiated between the

control group and the clinical groups but not among the clinical groups.

These findings indicate that children with CPS have significant difficulty with aspects of sustained attention and consistency of response regardless of the diagnosis of ADHD. Although AEDs have been found to affect attentional resources, 78% of children in this study were taking a medication not found to be significantly related to attentional problems [carbamazepine (CBZ)] and not the typical AEDs found to have such an effect (PB; 2,23,24). Polydrug therapy was related to significant attentional difficulties (2). No child in the current study was taking more than one AED. Thus it is unlikely that the AED was the cause of the attentional difficulty.

Children in both groups with CPS showed significant problems in staying focused and in their ability consistently to respond to the stimulus. It was not expected that those children without ADHD but with epilepsy would show such significant difficulty, and this finding alone begs the question of appropriate educational treatment beyond medication. In children with ADHD who are not receiving medication because of parent choice, interventions stressing problem solving and strategy generation have been helpful (25). These interventions also may be useful for children with epilepsy and their caretakers at home and school.

It is likely that children with CPS do show attentional difficulties, which may then contribute to, but not be the sole cause of memory difficulties. In children with attention problems not of sufficient severity for a diagnosis of ADHD but who have CPS, educational and therapeutic applications would appear to be warranted. At the very least, an evaluation of these children's attention deployment is warranted, even when ADHD is not suspected. As had been expected, children with epilepsy and ADHD performed the poorest on all measures and showed the most severe form of attention deficit.

We also hypothesized that administration of methylphenidate would improve the performance of both

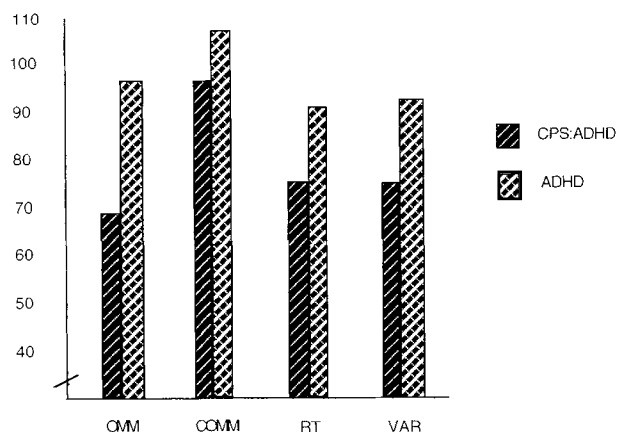


FIG. 2. TOVA with methylphenidate.

ADHD groups. This hypothesis was confirmed. Although the CPS/ADHD group did respond to the methylphenidate similar to the ADHD group, the CPS/ADHD group began with significantly poorer scores on the TOVA. The methylphenidate brought this group's scores within  $-1.5$  standard deviations from scores more than  $-3.5$  standard deviations below average. In contrast, the methylphenidate normalized the ADHD scores. A limitation of this study was that the control and CPS groups were not retested on the TOVA similar to the ADHD groups.

Conclusions from this study indicate that children with CPS should be evaluated directly for attention deficits regardless of a diagnosis of ADHD. The relation of attentional resources to CPS needs further investigation, as these difficulties frequently translate into difficulty in classroom functioning as well as in general adaptation in life, difficulties well documented to be present in children with CPS. Previous studies used teacher ratings and parent report to document attentional difficulties although not studying the child directly. This study is one of the first to report differences on a continuous performance test of attention.

There are several limitations to this study. One was the inability to evaluate the relation between epileptic foci and attentional difficulties. Of additional interest is whether the epileptic foci, be they frontal or temporal, correlate with attentional difficulties. Another limitation was that children were not provided with placebos to determine whether an effect was present because of expectation of the medication rather than from the medication alone. Further studies may clarify this issue. Continuing studies are being conducted to determine whether the improvement with methylphenidate as measured on the TOVA translates into improvement in the classroom.

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# Sustained Attention in Children With Specific Language Impairment (SLI)

Denise A. Finneran  
Alexander L. Francis  
Laurence B. Leonard

Purdue University, West Lafayette, IN

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**Purpose:** Information-processing limitations have been associated with language problems in children with specific language impairment (SLI). These processing limitations may be associated with limitations in attentional capacity, even in the absence of clinically significant attention deficits. In this study, the authors examined the performance of 4- to 6-year-old children with SLI and their typically developing (TD) peers on a visual sustained attention task. It was predicted that the children with SLI would demonstrate lower levels of performance in the absence of clinically significant attention deficits.

**Method:** A visual continuous performance task (CPT) was used to assess sustained attention in 13 children with SLI ( $M = 62.07$  months) and 13 TD age-matched controls ( $M = 62.92$  months). All children were screened for normal vision, hearing, and attention. Accuracy ( $d'$ ) and response time were analyzed to see if this sustained attention task could differentiate between the 2 groups.

**Results:** The children with SLI were significantly less accurate but not significantly slower than the TD children on this test of visual sustained attention.

**Conclusion:** Children with SLI may have reduced capacity for sustained attention in the absence of clinically significant attention deficits that, over time, could contribute to language learning difficulties.

**KEY WORDS:** specific language impairment (SLI), attention, information processing

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Children with specific language impairment (SLI) demonstrate marked language difficulties in the absence of typically associated factors such as hearing loss, neurological damage, or mental retardation (Leonard, 1998). Although these children have normal nonverbal IQ scores, researchers have found robust evidence of information processing deficits that may be attributed to limited working memory capacity (Bavin, Wilson, Maruff, & Sleeman, 2005; Ellis Weismer et al., 2000; Gillam, Cowan, & Marler, 1998; Hoffman & Gillam, 2004; Montgomery, 1995, 2000, 2003). In fact, Leonard et al. (2007) reported that the verbal working memory deficits exhibited by children with SLI accounted for a significant amount of the variance in composite language test scores.

In the investigation of working memory in the larger population, a number of models (e.g., Baddeley, 2001, 2003; Cowan, 1999, 2001, 2005) have identified attention as playing an important role in information processing. Attention is generally viewed as a limited-capacity system (e.g., Kahneman, 1973; Lavie, 2005; Lavie, Hirst, De Fockert, & Viding, 2004) composed of a number of different mechanisms including (but not exclusive to) sustained, selective, and divided attention (Leclercq, 2002). As attention is considered to be a limited-capacity system, so are the mechanisms that are associated with attentional control in these models (e.g., the central executive [Baddeley, 2003], the focus of attention

[Cowan, 2005]). It has been proposed that individual variations in working memory are associated with variations in attentional abilities (Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Bleckley, Conway, & Engle, 2001; see Cowan et al., 2005, and Engle, 2002, for reviews) and that factors that limit attentional capacity would impair performance on working memory tasks (see Baddeley, 2001, for a discussion).

Given that attention is considered to be a system that is deeply involved in information processing, and working memory is critical to language learning (Baddeley, 2003), it is not surprising, then, that attention is considered to play an important role in language processing (e.g., Conner, Albert, Helm-Estabrooks, & Obler, 2000; Posner, 1995). In the adult literature, for example, this relationship between attention and language learning has been demonstrated for natural languages (e.g., Guion & Pederson, 2007) as well as artificial languages (e.g., Toro, Sinnett, & Soto-Faraco, 2005).

In the literature on child development, the relationship between attention and language is usually addressed by examining the comorbidity of language impairments and attention deficits. There is robust evidence to suggest that children with language impairments have a higher incidence of attention deficits (e.g., Willinger et al., 2003), and children with clinical attention deficits have a higher incidence of language impairments (see Tannock & Schachar, 1996, for a review) than their peers. Some have proposed that clinical attention deficits and developmental language impairments are both a result of an underlying neurodevelopmental deficit, whereas others have proposed that deficits in one area may contribute to deficits in the other (see Redmond, 2005, for a review).

In light of the evidence for comorbidity of attention deficits and developmental language impairments, it is not surprising that researchers have begun to specifically relate attentional limitations to the language difficulties seen in SLI. For example, Helzer, Champlin, and Gillam (1996) suggested that the extra number of trials required by children with SLI to reach criterion on a test measuring auditory thresholds may have been due to difficulty sustaining attention to the stimuli. Similarly, Stark and Montgomery (1995) reported that children with language impairment (LI) demonstrated more behaviors associated with poor attention (e.g., playing with the headphones) than did typically developing (TD) children. The authors suggested that the reduced attention demonstrated by the LI group may have contributed to these children's difficulty in monitoring for words in sentences. Subsequently, Montgomery (2005, 2006) associated real-time language processing in children with SLI with their ability to allocate required attentional

resources. This association was also made by Campbell and McNeil (1985) in a study of language processing in children with acquired language impairment.

More explicit support for a possible relationship between SLI and deficits in basic attentional capacities may be found in a study by Im-Bolter, Johnson, and Pascual-Leone (2006). This study examined information processing and the role of executive function (i.e., the control of focused attention) in children with SLI as compared with age-matched TD peers. The authors reported significant group differences in attentional capacity, response inhibition, and working memory updating (an attentionally demanding process) as well as on visual and verbal processing tasks. The authors concluded that executive control of attention during information processing is an important factor in the relationship between information processing and language ability in SLI.

Finally, the proposed relationship between basic attentional processes and SLI is supported by the findings of Ellis Weismer, Plante, Jones, and Tomblin (2005). In this functional imaging study comparing children with SLI and TD peers performing linguistic tasks, children with SLI exhibited hypoactivation of parietal cortex, a brain region implicated in a variety of attentional processes, including sustained (Pardo, Fox, & Raichle, 1991), selective (Posner, 1990; Posner & Dehaene, 1994; Shaywitz et al., 2001), and divided attention (Shaywitz et al., 2001). This neuroanatomical evidence provides additional support for the hypothesis that a variety of attentional mechanisms may play a role in SLI, but this evidence does not clearly identify the contributions of specific types of attentional processes.

The current study specifically investigates sustained attention in children with SLI. *Sustained attention* has been described as the ability to continuously attend to input so that information in the input can be processed (Leclercq, 2002). It may be argued that sustained attention plays an important role in language acquisition, as children must sustain attention to the speech input, attending to relevant information and ignoring irrelevant information, in order to accurately perceive and correctly interpret the incoming linguistic information (see Montgomery, 2005, for a discussion of attentional mechanisms in sentence processing).

Given the role of sustained attention in information processing, it follows that there has been some recent attention given to sustained attention in children with SLI. In one study, Spaulding, Plante, and Vance (2008) investigated sustained selective attention in children with SLI and no diagnosis of attention-deficit disorder as compared with TD age-matched peers. In this study, the children were required to monitor (sustain attention to) a series of auditory or visual stimuli and press a

response button when they saw a predetermined target (i.e., select the target from among the distractors, or non-targets). The auditory stimuli were either linguistic (words) or nonlinguistic (familiar sounds; e.g., keys rattling). The visual stimuli involved an airplane executing a series of flying maneuvers. The stimuli were presented in a standard condition and in a degraded condition (with added white noise, either visual or auditory). Both accuracy and response time (RT) for correct responses were measured. The authors reported significant group differences in accuracy in the degraded condition for the auditory stimuli such that the children with SLI performed less accurately than the age-matched control group. This finding was taken to suggest that children with SLI may have difficulties with sustained selective attention for auditory information. Spaulding et al. (2008) reported that there were no significant group differences in RT for either the auditory or visual stimuli.

The current study examines visual sustained attention. The study was designed based on another recent study of visual sustained attention in children with normal language development. In this study, Rose, Murphy, Schickedantz, and Tucci (2001) investigated visual sustained attention in 7- and 8-year old children with normal language and no evidence of clinical attentional deficits. The children completed a 14-min continuous performance task (CPT) in which they were instructed to push a button on a response box as soon as a small square appeared on a computer screen but not to push the button when a large square appeared. Rose et al. reported that the children demonstrated the quickest RTs and highest accuracy when the stimuli were presented at a fast rate (90 events per 2-min epoch) rather than at a slow rate (20 events per 2-min epoch). The children also demonstrated a decrement in sustained attention in terms of speed and accuracy over time.

In the present study, children between 4 and 6 years of age with SLI and TD age-matched peers completed a visual CPT similar to that used by Rose et al. (2001). In this task, the children monitored for targets among a series of distractors over a 5-min period in both fast and slow presentation rate conditions.

As in the Rose et al. (2001) study, the stimuli for the current study were visual and nonlinguistic. Although Spaulding et al. (2008) did not find a group difference on the visual sustained selective attention task in their study, their findings need not necessarily predict the results of the current study. This is because the two studies used very different tasks. The task employed by Spaulding et al. involved watching an airplane executing a series of flying maneuvers; the children were instructed to press the response button when the plane executed a particular maneuver (e.g., flipping). In the current study, as in the Rose et al. (2001) study, the

stimuli were static red circles and squares; the children were instructed to press the response button when a circle appeared. Given that different tasks may impose different demands on information processing, and given that maintaining attention to dull tasks is more difficult than to more interesting ones, we expected the present task, using static balls and boxes, to impose greater demands on sustained attention than did monitoring the movements of an airplane in the Spaulding et al. study. Thus, it was predicted that the use of a simpler visual (and, therefore, more demanding) sustained attention task in the present study would more clearly distinguish children with SLI from their TD peers (see Corkum & Siegel, 1993, for a discussion on factors that impact performance on CPT tasks).

Visual rather than auditory stimuli were used so that performance on the sustained attention task would not be confounded with differences in auditory processing capabilities that are known to distinguish children with SLI from TD peers (Tallal & Piercy, 1973; Tallal, Stark, Kallman, & Mellits, 1981; Wible, Nicol, & Kraus, 2005). Nonlinguistic stimuli were used in this study under the assumption that the predicted attentional limitations are domain general rather than specific to linguistic input. This assumption was made based on the findings that information processing limitations in SLI are not exclusive to language processing tasks (e.g., word monitoring; Montgomery, 2000) but are also seen on tasks that involve information with minimal linguistic content (e.g., mental rotation [Johnston & Ellis Weismer, 1983]; arithmetic, pattern matching, and form completion [Windsor, Kohnert, Loxtercamp, & Kan, 2008]).

Three predictions were made at the start of the current study based on the findings of Rose et al. (2001) and current knowledge about SLI. The first two predictions pertain to language status: (a) The children with SLI would demonstrate poorer sustained attention when compared with the control group in terms of both accuracy and RT and (b) both groups would demonstrate a drop in performance over time, but the children with SLI would exhibit a greater decrement. These predicted group differences would lend further support to the growing body of evidence of attentional limitations in children with SLI who do not exhibit behaviors associated with clinically significant attention deficits. More specifically, the predicted group differences would indicate that children with SLI may have particular difficulty sustaining attention to the input, even for input with minimal nonlinguistic information. This finding, in combination with the findings of Spaulding et al. (2008), would suggest that children with SLI have limitations in sustained (and possibly selective) attention that may hinder their ability to process incoming information in different modalities. This, in turn, would be consistent with the notion of general processing limitations in SLI.

The final prediction pertains to the effect of event rate on performance. It was not clear whether the younger children in the current study would perform similarly to the older children in the Rose et al. study, so event rate was manipulated to determine which event rate would best facilitate performance. It was predicted that sustained attention would be best with the faster rate of stimulus presentation for all children.

## Method

### Participants

Twenty-six children participated in the current study, 13 with SLI (7 girls, 6 boys) and 13 with TD language skills (6 girls, 7 boys). Ten other children were recruited but did not complete the study. The 10 children who did not complete the study included 4 with SLI who were discontinued because they did not complete one of the testing sessions and 4 with SLI who were discontinued because they did not pass the attention screener (see the *Assessment* section). One TD child was discontinued because he did not appear to comprehend the task, and 1 TD child was discontinued due to low scores on a later language test. (A brief description of the children who did not complete the task is presented in the *Administration* section.) All children were of European descent and were living in monolingual English-speaking homes in Lafayette, Indiana, or in the surrounding area.

The 26 children included in this study were participating in a variety of other research experiments in the Child Language Development Laboratory at Purdue University at the time of this study. The 13 children with SLI were enrolled in a summer research program that provided speech therapy and a language-based classroom. The 13 children in the TD group were recruited separately, and their parents were reimbursed monetarily upon completion of the study. All children were given a "prize" of a small toy or book at the completion of each session.

*Subject matching.* The children who qualified as TD were selected to be an age match for a child with SLI if their chronological age fell within 2 months of the chronological age of a child in the SLI group. As a result, for each of the 13 children with SLI, there was an age-matched child in the TD group, and the two groups had comparable age distributions (SLI:  $M = 62.07$  months, range = 53–82 months; TD:  $M = 62.92$  months, range = 54–83 months).

*Assessment.* All children selected for this study participated in a speech and language assessment. To participate in the study, all children had to meet a series of requirements. All children had to pass a hearing screening at 25 dB (HL) for each ear at 500, 1000, 2000,

and 4000 Hz and had to demonstrate adequate oral structure and function for speech (Robbins & Klee, 1987). Furthermore, all children had to demonstrate age-appropriate performance (age deviation scores [ADS] of 85 or above) on a test of nonverbal intelligence (Columbia Mental Maturity Scale [CMMS]; Burgemeister, Blum, & Lorge, 1972). It should be noted that although all standard scores fell at or above the cutoff (85), the mean ADS score for the children in the SLI group ( $M = 108$ ,  $SD = 13$ , range = 85–135) was significantly lower than that for the children in the TD group ( $M = 120$ ,  $SD = 11$ , range = 106–140),  $t(24) = 2.46$ ,  $p = .02$ . The children who participated in the study all had a negative history of neurological impairment based on parent report and examiner observations.

In order to qualify as a participant in the SLI group, children had to score below the 10th percentile on the Structured Photographic Expressive Language Test–II (SPELT-II; Werner & Kresheck, 1983), a test of expressive morphology and syntax. To qualify as a participant in the TD group, the children had to score above the 10th percentile on this same test (all children in the TD group scored between the 21st and 100th percentile).

A measure of finite verb morphology known as *finite verb morphology composite* (FVMC; Leonard, Miller, & Gerber, 1999) was administered to assess expressive morphology in conversation. To qualify as a participant in the TD group, the children had to demonstrate age-appropriate expressive morphology skills on this measure (the children in the TD group achieved a mean score of 97%). Although this measure was not used to determine inclusion for the SLI group, the children with SLI demonstrated reduced performance on this measure ( $M = 68\%$ ) as compared with the children in the TD group.

*Conners' ADHD / DSM-IV Scales–Parent (CADS-P).* The CADS-P (Conners, 1997) was completed by participants' parents in order to screen for problems with attention and/or hyperactivity. Participants for both the SLI and TD groups were included only if their standardized scores (called *T*-scores) for the Attention-Deficit/Hyperactivity Disorder (ADHD) Index and *Diagnostic and Statistical Manual of Mental Disorders–IV (DSM-IV)* Total measures fell within the typical range (*T*-score at or below 65, as recommended by the author). As noted earlier, 4 of the 10 children who did not complete the study had met all other qualifications for inclusion in the SLI group but were disqualified from further participation as a result of these criteria (and were therefore not included in the group of 26 children participating in the study). The *T*-scores for the 26 children in the SLI and TD groups did not differ significantly on the ADHD Index,  $t(23) = 0.10$ ,  $p = .92$ , nor did they differ significantly on the DSM-IV Total measure,  $t(23) = 0.89$ ,  $p = .38$  (see Table 1 for a summary of assessment scores).

**Table 1.** Group means (and range) on diagnostic assessment tools.

Group	Age (in months)	Gender	MLU (words)	SPELT-II	FVMC	CMMS	CADS-P	
							ADHD Index	DSM-IV Total
SLI	62.07 (53–82)	6M/7F	4.25 (3.52–4.91)	2 (1–9)	68 (14–93)	108 (85–135)	48 (40–59)	48 (41–60)
TD	62.92 (54–83)	7M/6F	4.94 (4.07–7.06)	64 (21–100)	97 (95–100)	120 (106–140)	48 (40–59)	50 (42–58)

*Note.* MLU = mean length of utterance in number of words; SPELT-II = score on the Structured Photographic Expressive Language Test-II test of expressive morphology and syntax (see text) in terms of percentile rank; FVMC = score on the Finite Verb Morphology Composite test in terms of percentage of use in obligatory contexts; CMMS = score on the Columbia Mental Maturity Scale, a test of nonverbal intelligence (see text), in terms of age deviation score; CADS-P = Connors' ADHD/DSM-IV Scales-Parent; ADHD Index = ADHD Index subscale of the CADS-P test of attention (see text) in terms of *T*-score; DSM-IV Total = DSM-IV subscale of the CADS-P test of attention (see text) in terms of *T*-score; SLI = children with specific language impairment; TD = children with typical language development; M = male; F = female. Values are given in means; numbers in parentheses are group ranges.

## Procedure

The 26 participants (13 SLI, 13 TD) were tested on a CPT based on that of Rose et al. (2001). Where Rose and colleagues used a 14-min CPT with 7- and 8-year-old TD children, the current study used a CPT of abbreviated length (5 min), as the population tested was younger than that of Rose et al. (2001). A duration of 5 min was adopted, as there is evidence that TD children are able to complete a visual CPT of approximately 5 min in length by the age of 4;6 (years;months; Levy, 1980), which is comparable to the age range for the present study.

The CPT was run using the program E-Prime Version 1.1 (Schneider, Eschman, & Zuccolotto, 2002), which provides accurate millisecond timing by means of a separate response box. In the CPT, participants monitored for target stimuli (in this case, the appearance of a red circle, or “ball”) while ignoring distractor stimuli (the appearance of a red square, or “box”). The visual stimuli (circle, square) were created in Microsoft PowerPoint with the dimensions 1.25” × 1.25”. These stimuli were presented in the center of a white background covering the entire screen of a Dell computer monitor (9” × 12”). The children sat approximately 15” from the screen and were seated at a level such that the screen was at eye level or slightly below. However, the distance and relationship of the child to the screen varied, as some of the children moved around in their chairs while completing the task.

*Event rate.* The task consisted of two conditions based on rate of stimulus presentation: a fast event rate and a slow event rate condition. These two rate conditions were used in order to determine whether the fast or slow event rate would better facilitate performance. Rose et al. (2001) had tested both a fast and slow event rate with 7- and 8-year-old TD children and reported that performance was best in the fast rate condition. It was, however, unclear whether the fast event rate would best facilitate performance for the younger, language-impaired children participating in the present study.

In both event rate conditions, targets (balls) and distractors (boxes) were presented sequentially and appeared on the screen for 400 ms. The fast condition was conducted in a single 5-min session. Stimuli appeared at a rate of 40 tokens per minute with an interstimulus interval (ISI) of 1,100 ms. There were 16 targets and 24 distractors presented in random order each minute, so that 40% of all stimulus presentations were targets. A total of 200 stimuli were presented in the 5-min period (40 stimuli per minute × 5 min) with a total of 80 targets (16 targets × 5 min) and 120 distractors (24 distractors × 5 min).

Stimuli in the slow condition appeared at a rate of 10 tokens per minute; as a result, the ISI in the slow condition (5,600 ms) was greater than that in the fast condition (1,100 ms). As in the fast condition, 40% of the presentations were targets (4 targets, 6 distractors) in each minute. Therefore, in 5 min of the slow condition, there were a total of 20 targets (4 targets × 5 min) and 30 distractors (6 distractors × 5 min).

In order to facilitate analysis of performance across the rates of presentation, the slow condition was repeated over four 5-min sessions on separate days; as a result, in the slow condition there was the same total number of targets (4 sessions × 20 targets per session = 80) and distractors (4 sessions × 30 distractors per session = 120) as in the fast condition. This also allowed comparison of performance over the course of a 5-min session because there were as many target presentations in the first 1-min epoch of the fast condition session as there were cumulatively in the first 1-min epoch of each of the four slow sessions.

Each 5-min testing session (one fast, four slow) was conducted on a different day in order to lessen the impact of repeated presentations on performance. All participants completed the fast event rate condition on the first day of testing and the four slow sessions on the four subsequent sessions for a total of five testing sessions. The testing sessions were ordered in this way to allow for

a more stringent test of the prediction regarding the effect of rate. Based on the findings of Rose et al. (2001), it was originally predicted that all children would perform better in the fast event rate condition than in the slow event rate condition. By presenting the fast event rate condition on Day 1 and the slow event rate condition on Days 2–5, any improvement that resulted from repeated administrations would impact performance on the slow rate condition. Given that the slow event rate is the condition in which all children were predicted to perform the worst, this ordering ensures a more stringent test of the rate prediction.

*Administration.* For each session, the child was seated in a chair in front of a computer monitor, with the examiner sitting on the right side of the child and no other people in the room. The child was presented with a color photograph of a puppy on the monitor. They were told that the puppy liked only balls because they were fun to play with but did not like boxes. The children were instructed to push a button on a response box (Cedrus, Model RB-620; Cedrus Corp., San Pedro, CA) as soon as they saw the target (ball) but not to push the button when they saw the distractor (box). Both speed and accuracy were emphasized in the instructions. The children were told to continue with the task until the puppy returned to the screen.

On the first day of testing, the children were shown a drawing of a red circle (ball) and a red square (box) on pieces of paper prior to starting the task. They were asked to point to each as they were named. All children were able to identify the ball and the box correctly. Following this, two series of familiarization trials were completed in order to introduce the task to the child. No data were collected during familiarization, as the purpose was simply to allow the children to become familiar with the experimental task. The first set of familiarization trials were completed on the first day only. In these trials, the children were presented with a randomized sequence of four balls and four boxes, each of which were presented for up to 400 ms. A button push within this time resulted in immediate visual feedback (happy face for a target, sad face for a distractor). If no button was pushed during the stimulus presentation, visual feedback was presented at the end of the 400 ms (happy face for a distractor, sad face for a target). The clinician clicked the mouse to present the next stimulus and provided verbal feedback (e.g., “Good. You caught a ball for the puppy,” “That’s a box. The puppy does not want boxes.”).

The children then completed a second series of familiarization trials in order to practice the task without visual feedback. This 1-min session was presented after the first familiarization trials and then also at the beginning of each subsequent testing day in order to help

the child recall the task. In this second set of familiarization trials, children were presented with 8 balls and 12 boxes (67% targets) sequentially in randomized order (presentation time = 400 ms; ISI = 2,600 ms). This task employed a higher target probability than the experimental task in order to ensure optimal performance, as higher probabilities are associated with better signal detection and RT. A rate of 20 events per minute was selected for the 1-min familiarization task, as it fell between the high and low rates during testing and it was not clear which rate would facilitate the best performance with this population. The children were encouraged to complete the task independently and did not receive any visual feedback. Verbal feedback was provided as needed in order to encourage participation (e.g., “You are doing a good job”), to redirect (e.g., “Watch”), or to train (e.g., “Push the button only when you see a ball”).

The children completed testing immediately following the 1-min familiarization task for each experimental session. At the start of testing, the children were reminded of the instructions and were told to continue until the puppy reappeared on the screen. All children were praised for their participation and, as mentioned earlier, received a small prize (e.g., ball, Play-Doh, book) at the end of each testing session.

Following the terminology used in signal detection theory, the term *hits* is used to refer to the correct responses to stimulus-present trials (targets), and the term *false alarms* is used to refer to incorrect responses to stimulus-absent trials (distractors). For each experimental task, the numbers of hits and false alarms were recorded, as was the RT for hits. Accuracy, calculated using the signal detection theoretic statistic  $d'$ , was determined from the hit and false alarm rates (Macmillan & Creelman, 2005).

During the testing trials, the examiner provided verbal or visual feedback when needed to encourage participation and task completion. Prior to administration of the task, it was specified that the following feedback could be used if needed: instructions (provided when the child appeared not to understand the task; e.g., “Push the button only when you see the ball”), redirection (provided when the child appeared to be engaged in another activity and was thus distracted away from the task; e.g., playing with hands), and encouragement to continue the task (provided when the child appeared restless or increasingly distracted from the task; e.g., “You are finding lots of balls for the puppy,” “Almost done”). The testing sessions were video recorded (with the exception of one session due to an equipment malfunction) for later analysis of the examiner feedback.

Of the 10 children who did not complete the study (see *Participants* section), 5 had demonstrated difficulty

on the first day (the fast event rate condition) despite redirection and encouragement. These children were therefore discontinued from the study and are not included in the total sample size of 26 participants. These 5 children had met the criteria for either the SLI group (4) or TD group (1) and had passed the CADSP. One of the 5 children (SLI) exhibited noncompliant behaviors (i.e., he pushed the button repeatedly and announced that he was going to “catch” the boxes instead of the balls). The other 4 children (3 SLI and the 1 TD) demonstrated confusion and/or frustration with the task: One child (SLI) stopped participating (i.e., he stopped attending to the screen and pushing the response button) and stated that he did not want to participate any longer; three children (2 SLI, 1 TD) appeared to be confused by the task and sporadically engaged in other activities, although they never expressed a desire to stop the task. The data for these 5 children were judged to be missing or unusable for the fast event rate condition, and the children were therefore dropped from the study. All children received a “prize” and positive feedback regardless of their ability to complete the task. All 5 children continued to participate in other research projects.

## Results

Because the two language groups (SLI, TD) differed in terms of nonverbal IQ scores, the accuracy data set and RT data set were first analyzed with IQ as a covariate in two separate analyses of covariance (ANCOVAs) in order to determine whether IQ, rather than language status, might better predict performance on the sustained attention task for each data set. The data sets were then analyzed in analyses of variance (ANOVAs) without IQ as a covariate. An alpha level of .05 was used in all analyses.

## RT

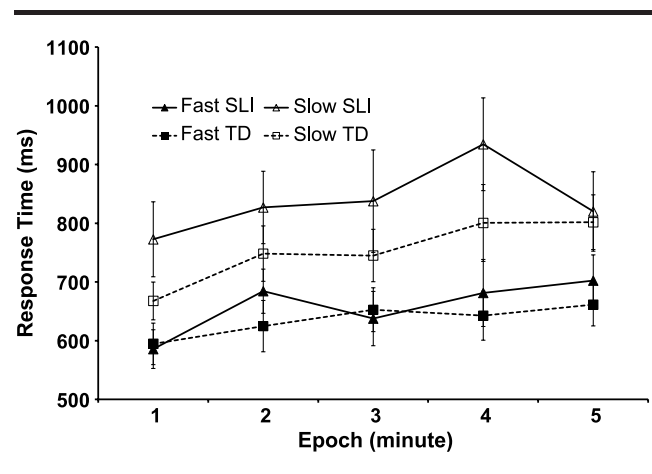
RT data were skewed to the right (Shapiro-Wilk,  $W = 0.99$ ,  $p = .009$ ), although all values were within three  $SD$ s of the mean. The statistical analyses were carried out on log-transformed values, but reported means, ranges,  $SD$ s, and standard errors ( $SE$ s) are untransformed. A mixed factorial ANCOVA was performed, with group (SLI, TD) as the between-subjects variable, event rate (fast, slow) and epoch (1st through 5th minute of testing) as within-subject variables, and nonverbal IQ scores as the covariate. The ANCOVA revealed no effect for group,  $F(1, 23) = 0.07$ ,  $p = .80$ , and no effect for IQ,  $F(1, 23) = 1.83$ ,  $p = .19$ . Based on these findings, it was determined that IQ did not predict performance as measured by RT on this sustained attention task.

Given that IQ was found not to be a significant factor in performance, the log-transformed RT data were then

analyzed without IQ as a covariate in an ANOVA, with group (SLI, TD) as the between-subjects variable and event rate (fast, slow) and epoch (1st through 5th minute of testing) as within-subject variables. This analysis also revealed no effect for group,  $F(1, 24) = 0.88$ ,  $p = .36$ . The analysis did reveal a significant main effect for rate,  $F(1, 24) = 246.19$ ,  $p < .0001$ ,  $\eta^2 = .91$  (large effect size), where RT values were higher (i.e., responses slower) in the slow rate condition ( $M = 796$  ms,  $SD = 181$ , range = 410–1,384 ms) than in the fast rate condition ( $M = 646$  ms,  $SD = 107$ , range = 364–1,062 ms). There was a main effect for epoch,  $F(4, 96) = 15.71$ ,  $p < .001$ ,  $\eta^2 = .40$  (large effect size); a Tukey’s honestly significant difference (HSD) post hoc analysis revealed that responses in Epoch 1 ( $M = 655$  ms,  $SD = 141$ , range = 396–1,062 ms) were significantly faster than those in Epoch 2 ( $M = 721$  ms,  $SD = 153$ , range = 464–1,098 ms,  $p < .001$ ), Epoch 3 ( $M = 718$  ms,  $SD = 177$ , range = 364–1,384 ms,  $p < .001$ ), Epoch 4 ( $M = 765$  ms,  $SD = 206$ , range = 401–1,285 ms,  $p < .001$ ), and Epoch 5 ( $M = 746$  ms,  $SD = 152$ , range = 443–1,249 ms,  $p < .001$ ), and RT for Epoch 3 ( $M = 718$  ms) was significantly faster than RT for Epoch 4 ( $M = 765$  ms,  $p = .048$ ). The Group  $\times$  Rate interaction was significant,  $F(1, 24) = 6.44$ ,  $p = .018$ ,  $\eta^2 = .21$  (large effect size), although a Tukey’s HSD post hoc analysis revealed no significant findings of interest (SLI fast vs. TD fast,  $p = .97$ ; SLI slow vs. TD slow,  $p = .51$ ). The Rate  $\times$  Epoch interactions,  $F(4, 96) = 1.75$ ,  $p = .15$ ; Group  $\times$  Epoch interactions,  $F(4, 96) = 1.30$ ,  $p = .28$ ; and Group  $\times$  Rate interactions,  $F(4, 96) = 2.13$ ,  $p = .08$ , were not significant (see Figure 1).

In examining these findings, it is notable that although the two language groups differed in terms of mean nonverbal IQ scores, IQ was not a significant

**Figure 1.** Mean response time (in ms) by epoch for children with specific language impairment (SLI) and age-matched typically developing (TD) controls at both fast and slow event rates (scale does not start at zero). Error bars indicate standard error of the mean.



factor when included in the analysis. Furthermore, results suggest that the model that excluded IQ from the analysis was, in fact, the preferred model for this data set. A comparison of the Akaike Information Criterion (AIC)<sup>1</sup> for the model with IQ (ANCOVA) and the model without IQ (ANOVA) was worse (i.e., larger; -101.0) when IQ was included as a variable and better (i.e., smaller; -102.7) when IQ was not included as a variable in the statistical model. Therefore, the addition of IQ as a variable in the model resulted in a small but quantifiable reduction in the goodness-of-fit of the model.

## Accuracy

Accuracy data were also non-normally distributed (Shapiro-Wilk,  $W = 0.99, p = .011$ ), but again, all values were within three *SDs* of the mean. Following the procedures outlined by Kirk (1995, p. 105), it was determined that a square-root transformation was most appropriate for these data. As with RT, all reported means, *SDs*, and *SEs* are untransformed, and an alpha level of .05 was used in all analyses.

Given that the two language groups (SLI, TD) differed in terms of nonverbal IQ scores, the accuracy data were first analyzed to determine whether IQ, rather than language status, might better predict performance on the sustained attention task. The square-root-transformed accuracy data were analyzed in a mixed factorial ANCOVA, with group (SLI, TD) as the between-subjects variable, event rate (fast, slow) and epoch (1st through 5th minute of testing) as within-subject variables, and nonverbal IQ scores as the covariate. Results showed a significant main effect for group,  $F(1, 23) = 11.31, p = .003, \eta^2 = .33$  (large effect size), where accuracy ( $d'$ ) was higher for the TD group ( $M = 2.89, SD = 0.78, \text{range} = 1.31\text{--}3.27$ ) than for the SLI group ( $M = 2.22, SD = 0.43, \text{range} = 0.11\text{--}3.27$ ). There was no effect for IQ,  $F(1, 23) = 0.30, p = .59$ . Based on these findings, it was determined that IQ did not predict performance as measured by accuracy ( $d'$ ) on this sustained attention task.

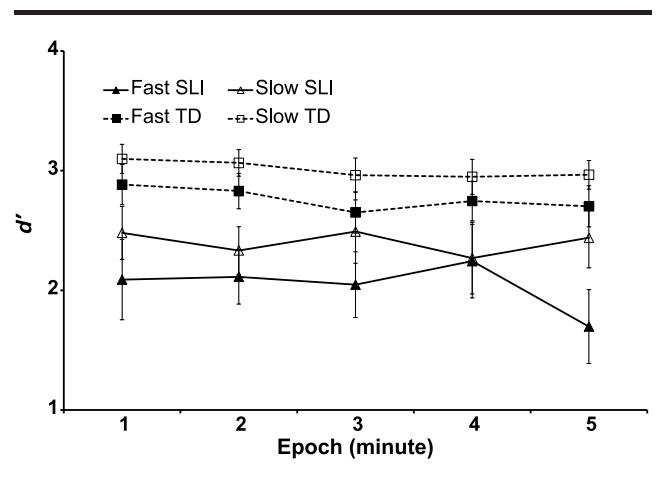
Given that IQ was found not to be a significant factor in performance, the square-root-transformed accuracy data were analyzed without IQ as a covariate in a mixed factorial ANOVA, with group (SLI, TD) as the between-subjects variable and event rate (fast, slow) and epoch (1st through 5th minute of testing) as within-subject variables. Results again showed a significant main effect for group,  $F(1, 24) = 16.17, p < .001, \eta^2 = .40$  (large

effect size), where accuracy ( $d'$ ) was higher for the TD group ( $M = 2.89, SD = 0.78, \text{range} = 1.31\text{--}3.27$ ) than for the SLI group ( $M = 2.22, SD = 0.43, \text{range} = 0.11\text{--}3.27$ ). There was also a main effect for rate,  $F(1, 24) = 28.21, p < .001, \eta^2 = .54$  (large effect size), in which accuracy for the set of all children was higher in the slow rate condition ( $M = 2.71, SD = 0.63, \text{range} = 0.71\text{--}3.27$ ) than the fast rate condition ( $M = 2.40, SD = 0.76, \text{range} = 0.11\text{--}3.27$ ). There was no effect for epoch,  $F(4, 96) = 1.30, p = .28$ , and no significant Rate  $\times$  Group interactions,  $F(1, 24) = 2.61, p = .12$ ; Rate  $\times$  Epoch,  $F(4, 96) = 1.55, p = .19$ ; Epoch  $\times$  Group,  $F(4, 96) = 0.59, p = .67$ ; or Rate  $\times$  Epoch  $\times$  Group,  $F(4, 96) = 1.17, p = .33$  (see Figure 2).

As for the RT data, goodness-of-fit was better (i.e., AIC was smaller) for the statistical model (ANOVA) that did not include IQ as a variable than for the ANCOVA that did include IQ (ANOVA: -102.7; ANCOVA: -101.0). Therefore, as for the RT data, the addition of IQ as a variable actually resulted in a reduction in the goodness-of-fit of the model.

*Hits and false alarms.* Performance on an attentional task can be influenced both by the ability to correctly respond to target stimuli and by the ability to inhibit incorrect responses to distractors. In terms of signal detection theory (Macmillan & Creelman, 2005), these are measured as hit rate (proportion of correct responses to targets) and false alarm rate (proportion of incorrect responses to distractors). Note that because the number of responses that are made to targets is independent of the number of responses that may be made to distractors, hit rate and false alarm rate are mathematically independent. The number of false alarms has traditionally been considered a rough measure of impulsivity, such that more impulsive individuals are more likely to exhibit a heightened rate of false alarms (see

**Figure 2.** Mean accuracy ( $d'$ ) by epoch for children with SLI and age-matched TD controls at both fast and slow event rates (scale does not start at zero). Error bars indicate standard error of the mean.



<sup>1</sup>The AIC is a number, based on residual sums of squares, that is used as a criterion for choosing between competing statistical models for the one that has the best goodness-of-fit. Given a particular set of data, the model having the lowest AIC is the preferred model for that data. AIC is generally expected to improve (decrease) with the addition of variables in a model (Davis, 2003).



Corkum & Siegel, 1993, and National Institute of Child Health and Human Development [NICHD] Early Child Care Research Network, 2003, for a review).

Thus, the false alarm data were analyzed in an attempt to determine whether the group differences in performance may be associated with poorer impulse control in the children with SLI. False alarms were totaled for each rate condition for each child and were analyzed in a mixed factorial ANOVA, with subject (SLI, TD) as the between-subjects variable and rate (fast, slow) as a within-subjects variable. There was a main effect for group,  $F(1, 24) = 6.30, p = .019, \eta^2 = .21$ , in which the children in the SLI group had significantly more false alarms ( $M = 12.08, SD = 10.49, \text{range} = 4\text{--}58$ ) than the children in the TD group ( $M = 5.58, SD = 4.35, \text{range} = 4\text{--}32$ ). There was a main effect for rate,  $F(1, 24) = 9.02, p = .006, \eta^2 = .27$ , in which there were significantly more false alarms in the fast rate condition ( $M = 11.23, SD = 9.52, \text{range} = 2\text{--}38$ ) than in the slow rate condition ( $M = 6.42, SD = 6.94, \text{range} = 1\text{--}26$ ). The Rate  $\times$  Group interaction was not significant,  $F(1, 24) = 0.88, p = .36$ . These findings suggest that the children with SLI were, overall, more impulsive than the children in the TD group and that both groups of children demonstrated increased impulsivity when the event rate was higher (see Figure 3).

Hits were also analyzed as a rough measure of inattention (see Corkum & Siegel, 1993, for a discussion). The total number of hits were calculated for each event rate for each child, and the data were analyzed in a mixed factorial ANOVA, with subject (SLI, TD) as the between-subjects variable and rate (fast, slow) as a within-subjects variable (see Figure 3). Analysis of the data for hits revealed a main effect for group,  $F(1, 24) = 8.52, p = .008, \eta^2 = .26$ , in which the children in the SLI

group had significantly fewer hits ( $M = 62.62, SD = 12.92, \text{range} = 36\text{--}79$ ) than the children in the TD group ( $M = 72.81, SD = 5.31, \text{range} = 62\text{--}80$ ). There was no effect for rate,  $F(1, 24) = 3.37, p = .079$ , and the Rate  $\times$  Group interaction was not significant,  $F(1, 24) = 0.004, p = .95$ . These findings suggest that the children with SLI were not only more impulsive but also less attentive on the sustained attention task (see Figure 3). The findings also indicate that the rate manipulations did not have a significant effect on the number of hits for either group. An analysis of the total number of responses for each group (hits and false alarms) revealed that the children in the SLI group ( $M = 149, SD = 30, \text{range} = 113\text{--}195$ ) did not differ significantly from those in the TD group ( $M = 157, SD = 11, \text{range} = 140\text{--}172$ ),  $t(24) = 0.84, p = .41$ .

**Accuracy and language.** Given the finding that the children with SLI performed at a lower level of accuracy than the children in the TD group, an analysis was conducted to determine if there was a correlation between accuracy scores on the sustained attention task (mean  $d'$  scores for each child) and the standard scores on the Peabody Picture Vocabulary Test–Third Edition (PPVT-III; Dunn & Dunn, 1997). This receptive vocabulary test was used in the correlation, as it was not used to determine inclusion in the SLI or TD language groups. A Pearson product-moment analysis using the non-transformed  $d'$  data revealed a moderate correlation of  $.56, t(24) = 3.21, p < .01$ , suggesting that there may be an association between sustained attention and receptive vocabulary skills.

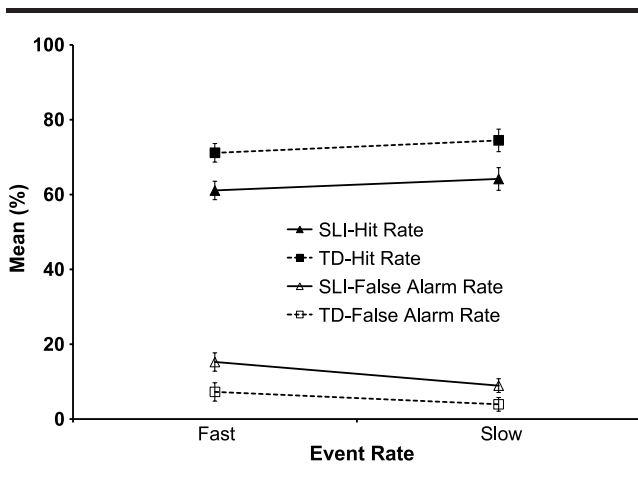
### Effects of Repeated Administrations

The RT data and accuracy data for the slow event rate were analyzed to determine whether repeated administrations of this task had a significant effect on performance.

**RT.** Mean RT was calculated for each of the four slow event rate sessions per child. The data were analyzed in a mixed factorial ANOVA, with group (SLI, TD) as the between-subjects variable and day (1–4) as a within-subjects variable. There was no effect for group ( $M_{\text{SLI}} = 842, SD = 216, \text{range} = 435\text{--}1,327$ ;  $M_{\text{TD}} = 749, SD = 141, \text{range} = 517\text{--}1,159$ ),  $F(1, 24) = 2.41, p = .13$ , nor for day, ( $M_{\text{Day 1}} = 763, SD = 178, \text{range} = 526\text{--}1,160$ ;  $M_{\text{Day 2}} = 785, SD = 204, \text{range} = 439\text{--}1,258$ ;  $M_{\text{Day 3}} = 796, SD = 169, \text{range} = 474\text{--}1,240$ ;  $M_{\text{Day 4}} = 838, SD = 198, \text{range} = 512\text{--}1,327$ ),  $F(3, 72) = 1.74, p = .17$ , and the Group  $\times$  Day interaction was not significant,  $F(3, 72) = 0.53, p = .67$ . The results of these analyses did not change in statistical significance when log-transformed values, rather than nontransformed RT values, were analyzed.

**Accuracy.** Mean accuracy ( $d'$ ) was calculated for each of the four slow event rate sessions per child. The data were analyzed in a mixed factorial ANOVA, with group

**Figure 3.** Mean number of hits and mean number of false alarms by group. Error bars indicate standard error of the mean.



(SLI, TD) as the between-subjects variable and day (1–4) as a within-subjects variable. There was an effect for group,  $F(1, 24) = 13.39$ ,  $p = .001$ ,  $\eta^2 = .36$ , in which accuracy for the children in the SLI group ( $M = 2.50$ ,  $SD = 0.75$ , range = 0.60–3.48) was significantly lower than that for the TD group ( $M = 3.18$ ,  $SD = 0.40$ , range = 2.15–3.48). There was no effect for day ( $M_{\text{Day } 1} = 2.74$ ,  $SD = 0.65$ , range = 2.27–3.48;  $M_{\text{Day } 2} = 2.89$ ,  $SD = 0.76$ , range = 2.51–3.48;  $M_{\text{Day } 3} = 2.82$ ,  $SD = 0.64$ , range = 2.61–3.48;  $M_{\text{Day } 4} = 2.90$ ,  $SD = 0.72$ , range = 2.15–3.48),  $F(3, 72) = .66$ ,  $p = .58$ , and the Group  $\times$  Day interaction was not significant,  $F(3, 72) = 0.29$ ,  $p = .83$ . The results of these analyses did not change in statistical significance when square-root-transformed values, rather than non-transformed accuracy values, were analyzed.

## Examiner Feedback

The tapes for the 26 children included in the study were later reviewed, and instructor feedback (with time of occurrence, in ms) was logged. The total number of instances of examiner feedback was then calculated for each 1-min epoch for each of the 26 children. The data were analyzed in a mixed factorial ANOVA, with group as the between-subjects variable and rate (fast, slow) and epoch (1–5) as within-subjects variables. (The 1 child that was missing one taped session due to the video camera malfunction was excluded from this analysis.) There was a main effect for group,  $F(1, 23) = 6.80$ ,  $p = .016$ ,  $\eta^2 = .23$ , in which the children in the SLI group received more feedback overall ( $M = 2.3$ ,  $SD = 3.07$ , range = 0–58) as compared with the children in the TD group ( $M = 0.73$ ,  $SD = 1.47$ , range = 0–33). There was no effect for rate,  $F(1, 23) = 2.90$ ,  $p = .10$ , nor for epoch,  $F(4, 92) = 1.92$ ,  $p = .33$ , and there were no significant interactions: Rate  $\times$  Group,  $F(1, 23) = 0.03$ ,  $p = .86$ ; Rate  $\times$  Epoch,  $F(4, 92) = 0.77$ ,  $p = .54$ ; Epoch  $\times$  Group,  $F(4, 92) = 1.96$ ,  $p = .14$ ; Rate  $\times$  Epoch  $\times$  Group,  $F(4, 92) = 0.81$ ,  $p = .52$ . These results indicate that the children with SLI received more feedback overall than the children in the TD group but that there were no significant differences in the amount of feedback either group received across input rate conditions or epochs.

## Discussion

Three predictions were made at the start of this study: (a) The children with SLI would demonstrate poorer sustained attention with slower and less accurate responses than the TD children; (b) both groups would demonstrate a sustained attention decrement across the five 1-min epochs where accuracy ( $d'$ ) would drop and responses (RT) would slow, but the children with SLI would present with a greater decrement in sustained attention as compared with the TD children; and (c) performance

(RT,  $d'$ ) would be best in the fast rate condition for both language groups.

## Group

The first prediction addressed group differences. Analysis revealed that although the children with SLI were not slower than the TD children, they were consistently less accurate (i.e., the children with SLI demonstrated poorer sustained attention) across both epoch and rate manipulations. Several considerations are discussed with regard to the presence or absence of significant group effects.

*Performance and nonverbal IQ scores.* As noted previously, the children in the SLI group had significantly lower nonverbal IQ scores as compared with the children in the TD group. There are inconsistent findings in the literature regarding the relationship between intelligence and sustained attention, although there is some evidence of a positive relationship between these two factors in preschool-age children (for reviews, see Berch & Kanter, 1984; Corkum & Siegel, 1993). Nonverbal IQ scores were therefore entered as a covariate in the analyses for both the RT and accuracy data in order to determine whether IQ, rather than language status, might better predict performance on the sustained attention task for each data set. Results indicated that IQ did not predict performance as measured by RT or by accuracy on this sustained attention task.

*Accuracy and receptive vocabulary scores.* There was a moderate correlation between accuracy on the sustained attention task and receptive vocabulary scores, suggesting that there may be an association between the children's performance on this nonverbal test of attention and receptive vocabulary abilities (although a causative relationship cannot be determined from the analysis).

*Children not included in the study.* As discussed previously, of the 10 children who were discontinued from the study, 8 were children who had qualified for the SLI group but had been discontinued because they failed the attention screener (4 children) or demonstrated significant difficulty with the task (4 children). The behaviors demonstrated by these children during the sustained attention task (e.g., disengaging from the task) or reported by parents on the CADS-P (e.g., easily frustrated) are typically associated with attentional difficulties. It seems possible, then, that there would have been an even greater difference in accuracy between the two language groups if these 8 other children had completed the task. As is, even with the conservative criteria used for inclusion (including equivalent attention scores on the CADS-P across the two language groups), the children with SLI still demonstrated reduced sustained attention as compared with their TD peers. This suggests that

children with SLI appear to demonstrate subtle deficits in sustained attention that may not be reflected in broader measures of attention such as the CADSP.

*Accuracy and inhibition.* There is evidence that children have difficulty inhibiting habituated responses as compared with adults (e.g., Harnishfeger & Bjorklund, 1994) and that children with SLI have even greater difficulty inhibiting their responses than their peers on tasks of verbal working memory (e.g., Marton, Kelmenson, & Pinkhasova, 2007; Marton & Schwartz, 2003). Although the present task was not explicitly designed to assess response inhibition, the false alarm data were analyzed as a rough measure of impulsivity in order to determine whether the children with SLI had demonstrated greater impulsivity in responding as compared with the TD group. Analyses revealed that there were more false alarms for the SLI group than the TD group. Analysis of the hit data revealed, conversely, that there were fewer hits for the SLI group than the TD group. These findings suggest that, as a group, the children with SLI demonstrated increased impulsivity and greater inattention.

The set of all children had a higher number of false alarms in the fast rate condition than in the slow rate condition. This is consistent with previous findings that children with and without attention deficits made fewer false alarms when the rate of stimuli presentation was slower (and, thus, the ISI was longer; see Corkum & Siegel, 1993, for a discussion on factors that influence performance on sustained attention tasks).

*RT.* It was predicted that the children with SLI would demonstrate reduced sustained attention in the form of slower reaction times as well as reduced accuracy. Analysis revealed no significant group differences, however. The lack of RT differences between groups may be surprising in light of the literature that reports generalized slowing in processing speed in SLI (e.g., Kail, 1994; Miller, Kail, Leonard, & Tomblin, 2001). However, there is evidence that children with SLI may not demonstrate reduced RTs as compared with their peers, and this may be especially true with respect to attentionally demanding tasks. For example, Im-Bolter et al. (2006) found no group differences in RT between children with SLI and TD children on a variety of tests of executive function and attentional inhibition. Similarly, in one recent study on sustained selective attention in SLI, Spaulding et al. (2008) reported that there were no RT differences between a group of preschool-age children with SLI and TD peers.

## Epoch

The second prediction addressed the hypothesized sustained attention decrement. It was expected that both groups would demonstrate a performance decrement

(reduced accuracy, increased RT) across the five 1-min epochs in both rate conditions but that the children with SLI might show a greater decrement over time than would the TD children. Analysis revealed that, on average, children in both groups were fastest in Epoch 1, followed by a trend of slowing RT, and another significant decrement at Epoch 4. Alternatively, accuracy levels were consistently maintained across all five epochs for both rate conditions. These findings reveal that the children slowed but did not lose accuracy as the 5-min task progressed. This slowing of responses may have reflected increasing difficulty with sustaining attention over time.

These findings generally support the initial prediction of a performance decrement, although a significant decrement was not observed across all five epochs. It is important to note that although the decrement is well documented in adults, it is not consistently documented in children (see Berch & Kanter, 1984, and Corkum & Siegel, 1993, for a discussion). This may be due in part to the abbreviated nature of the CPTs used with children. Whereas adult research uses CPTs that can vary in duration from 10 min (Ballard, 2001) to up to 40 min (Smit, Eling, & Coenen, 2004) or more, studies with children typically use abbreviated monitoring tasks (e.g., Rose et al., 2001; see Corkum & Siegel, 1993, for a review). As discussed previously, a 5-min CPT was used in the current study because there is evidence that children of this age are able to complete a visual CPT of this length (Levy, 1980), and it was expected that the population tested would have difficulty completing anything significantly longer.

Another possible age-related reason for the absence of a significant decrement across the 5-min task relates to the need for instructor feedback during the task. The children who had participated in this study were younger than those tested by Rose et al. (2001). These younger children in the current study had required some amount of feedback to participate in and complete the sustained attention task. This type of feedback was not reported to be used by Rose et al. and is not typically used in adult studies of sustained attention. It is possible that although there was not a significant increase in feedback across the five 1-min epochs, the presence of feedback in the five epochs may have facilitated performance to the degree that any decrement in performance over time was reduced in magnitude.

As discussed previously, a number of children were discontinued from the task as a result of behaviors (reported or observed) that are typically associated with attentional difficulties. Given this, it is also possible that there would have been a more significant decrement in performance across the five 1-min epochs if these children had completed the task. Finally, it is possible that the absence of a significant decrement across the 5-min task may not be an artifact of the task but, rather,

may reflect an aspect of the developmental trajectory of sustained attention.

## Rate

The third prediction addressed the effect of event rate on performance. Rose et al. (2001) had reported that young school-age TD children performed best (i.e., faster RTs, higher accuracy) in the fast rate condition. The effect of event rate was examined in the current study in order to determine how event rate affects the performance of younger children with and without language impairments. It was predicted that performance would be best in the fast rate condition. There were no specific predictions with regard to a Group  $\times$  Rate Condition interaction, as it was not clear which event rate would better facilitate performance for these children.

Analyses revealed that both groups responded faster in the fast rate condition, although they were more accurate in the slow rate condition. These findings are consistent with the adult literature in which an inverse relationship between event rate and performance accuracy in sustained attention tasks is well documented (Leclercq, 2002; Warm & Jerison, 1984). This suggests that this pattern of behavior may be associated with the experimental task and was not a consequence of the participants' age or language status.

In the adult literature, researchers have attempted to explain the inverse relationship between event rate and performance accuracy in a number of ways. It has been proposed that improved accuracy with a slower event rate may be a direct result of having fewer signals to detect overall, leading to improved ability to distinguish signals from distractors (Guralnick, 1973, as cited by Warm & Jerison, 1984, p. 40). It has also been proposed that a slower event rate allows for more time to make a decision (supported by the observation of longer RTs), thus improving accuracy (Leclercq, 2002; Warm & Jerison, 1984).

There were no significant Group  $\times$  Rate Condition interactions. The Rate  $\times$  Group interaction approached significance for the RT data, but a post hoc analysis revealed no significant differences of interest (i.e., the two language groups did not differ significantly in either rate condition). Thus, it appears that the event rate manipulations did not have a differential effect on RTs according to language status. It should be noted that there was also not a significant difference in RT between the two groups overall. As previously discussed, the lack of significant group differences in RT is consistent with the findings of Spaulding et al. (2008) in their study of sustained selective attention. These findings may be taken to suggest that on tests of sustained attention, the measurement of RT may not consistently differentiate children with LI from their TD peers.

## Summary

In the present study, the children with SLI demonstrated reduced visual sustained attention as compared with their TD peers. The findings of the present study are significant in several ways. For one, it adds to the body of literature that suggests the presence of attentional limitations in children with LI who do not demonstrate behaviors associated with clinical attention deficits. More specifically, the findings indicate that children with SLI may, in fact, have difficulty with sustained attention to visual stimuli as well as to auditory stimuli (Spaulding et al., 2008).

The finding of difficulties in visual sustained attention, in conjunction with the reported difficulties in auditory sustained attention tasks (Spaulding et al., 2008), supports the proposal that the general processing deficits in SLI may be associated with concurrent limitations in sustained attention. It is not clear whether the language processing problems and attentional limitations have a causal relationship or whether they both result from an underlying neurodevelopmental deficit. Although the limited nature of the present results, derived from a single experiment with a small number of children from two relatively homogeneous cohorts, makes it difficult to do more than speculate in general terms, current understanding of the role of attention in language learning suggests that the present results are consistent with the following hypotheses regarding the potential role of sustained attention limitations in SLI.

Given that working memory models typically associate the limited nature of information processing with limitations in the availability of attentional resources such as selective (e.g., Conway, Cowing, & Bunting, 2001) and sustained attention (e.g., Engle et al., 1999), it seems possible that any constraints on these attentional mechanisms, such as limitations in the ability to sustain focused attention, would therefore constrain information processing. Thus, limitations in attentional resources (such as the ability to sustain attention) could contribute to deficits in information processing capacity or speed which, in turn, could constrain language learning. Following this line of reasoning, limitations in sustained attention could, over time, contribute to the development of language deficits by virtue of their interference with information processing systems necessary for normal language development.

## Clinical Implications

Attentional factors—particularly, subclinical limitations in attentional capacity—have not yet received much examination in the SLI literature. The current findings suggest that children with SLI may, in fact, demonstrate limitations in their ability to sustain attention, even in the absence of clinically diagnosable attention deficits. Given the fundamental role of attention

in language processing, the results of this study support the hypothesis that subclinical limitations in attention might be a part of the SLI profile.

It is notable that the children with SLI in this study demonstrated significantly reduced sustained attention in an environment controlled for distraction where they were explicitly instructed to attend to the stimuli. It seems likely that if these children demonstrated reduced sustained attention in this more optimal, if more artificial, environment, then they might demonstrate the same or even greater levels of difficulty in more natural settings. It is important, therefore, to be sensitive to the impact that limitations in sustained attention may have on developmental language problems even in the absence of clinically diagnosable attention deficits.

Based on the findings of the current study, it may be possible to facilitate sustained attention in learning environments. When clinicians and educators design tasks to teach specific skills or knowledge, they may improve the child's performance and learning by (a) controlling the rate of information that is being presented; (b) reducing the amount of time in which the children must sustain attention to a task (e.g., shortening task length, increasing the frequency of breaks within a task, increasing active child participation); and (c) providing feedback to facilitate participation and, possibly, the level of sustained attention to the task.

## Conclusion

This study provided evidence that subclinical limitations in sustained attention may be one underlying component of developmental language disorders. Further research on the relationship between attentional capacity and language acquisition will help to broaden our understanding of how attentional factors may contribute to language difficulties. Specifically, more investigation is needed into the roles that the various forms of attention (e.g., sustained, divided) play in language learning and how limitations in these attentional mechanisms may impede learning about different aspects of language (e.g., phonological, semantic, syntactic). Given that sustained attention improves with age (see Berch & Kanter, 1984, for a discussion), further research is also needed to examine how the relationship between attention and language learning changes over time in children with LI. This better understanding of the role of attention in language learning in SLI may then be applied by clinicians and educators to the assessment and treatment of children with SLI.

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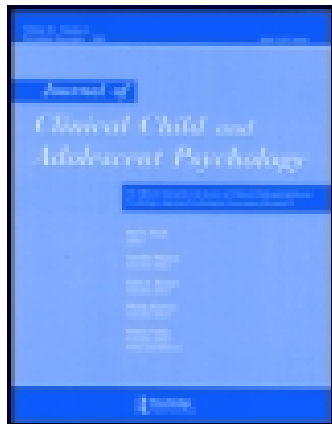
Contact author: Denise A. Finneran, who is now with the University of South Carolina, Department of Communication Sciences and Disorders, Williams Brice Building, 6th Floor, 1621 Greene Street, Columbia, SC 29208.  
E-mail: dfinneran@sc.edu.

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## Sustained and Selective Attention in Boys With Attention Deficit Hyperactivity Disorder

Kim Hooks, Richard Milich, and Elizabeth Pugzles Lorch  
*University of Kentucky*

*Attempted to clarify the nature of the sustained and selective attention deficits implicated in attention deficit hyperactivity disorder (ADHD). Specifically, performance on the Continuous Performance Test (CPT; Sergeant & van der Meere, 1990) and speeded classification task was assessed for a group of 7- to 12-year-old ADHD boys and their same-aged normal peers. Results of the CPT indicated that both perceptual sensitivity and omission errors increased over time for the ADHD boys to a greater degree than for the control boys, findings indicative of a sustained attention deficit. Results of the speeded classification task indicated that ADHD children's performance was not as efficient as normal children. However, there was no evidence for a selective attention deficit. Findings are discussed in terms of a process-energy model of attention.*

Two types of attentional deficits have been implicated in attention deficit hyperactivity disorder (ADHD). The first of these is a sustained attention deficit: the inability to maintain attention over time. ADHD children appear under some conditions to have more difficulty in maintaining attention over time than their normal counterparts (Nuechterlein, 1983). The second type of deficit is a selective attention deficit: the inability to preferentially attend to relevant aspects of a task and to ignore irrelevant information. At present, the evidence for a selective attention deficit in ADHD children is contradictory. Douglas (1983) proposed the deficit occurs only in specific situations such as when irrelevant information is highly appealing. Ceci and Tishman (1984) proposed that ADHD children might be better conceptualized as having "diffuse" attention. They only exhibit a selective attention deficit when the task is too difficult or unfamiliar.

### A Process-Energy Model of Attention

According to Sergeant and van der Meere (1990), sustained and selective attention deficits can be understood by using a process-energy model of information processing. This model considers the demands a task imposes on information processing as well as the energy resources needed to meet those demands. The process-energy model is broken down into four stages

of information processing that are related to three separate pools of energy: The information-processing stages are encoding, memory search, decision making, and response output; the energy pools are arousal, activation, and effort (Posner, 1978; Sanders, 1983; Sergeant & van der Meere, 1990).

The first stage of information processing, encoding, is connected with the first energy pool, arousal. Arousal is determined by stimulus intensity, so that more arousal is needed to encode degraded, brief, or unfamiliar stimuli (Sergeant & van der Meere, 1990). The second and third stages of information processing are memory search and decision making. In these stages a particular stimulus in the environment is compared to items in memory, and a decision is made as to which memory item matches the stimulus. Effort is sometimes implicated specifically in the decision making stage (Posner, 1978; Sanders, 1983). It has also been defined as the energy required to modulate the arousal and activation pools (Sanders, 1983; Sergeant & van der Meere, 1990). The fourth stage of processing, response output, is associated with activation. Activation is determined by such things as event rate (the time interval between stimuli) and foreperiod (the time between a warning and a target signal; Sanders, 1983).

### Sustained Attention

#### Continuous Performance Test

As previously noted, sustained attention is the ability to maintain attention over time (Douglas, 1983). One well-known measure of sustained attention is the Con-

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Requests for reprints should be sent to Richard Milich, Department of Psychology, University of Kentucky, Lexington, KY 40506.

tinuous Performance Test (CPT; Sergeant & van der Meere, 1990). In this vigilance task, stimuli (e.g., letters) are flashed one at a time on the computer screen and the subject is instructed to respond when a particular stimulus (e.g., letter) or pattern of stimuli appears. Errors on the CPT are divided into two types. *Omission errors* occur when there is a failure to respond to a correct target sequence and are thought to reflect problems with inattention. *Commission errors* occur when a response is made in the absence of a correct target sequence and are often thought to reflect problems with impulsivity.

Failure to maintain attention over time precipitates a performance decline that is referred to as a sustained attention decrement. Traditionally on the CPT, sustained attention has been measured by increases in omission and commission errors over time. More recently, however, two other measures have gained favor. These are perceptual sensitivity ( $d'$ ) and decision criterion ( $\beta$ ). The former measure refers to the ability to distinguish the target from irrelevant stimuli and, according to the process-energy model, is assumed to be an index of arousal. The latter measure refers to the tendency to become more conservative in responding with time and is thought to reflect changes in effort as well as activation (Sanders, 1983). A decrease in  $d'$  or an increase in  $\beta$  over time both reflect a sustained attention decrement. If ADHD children experience a greater  $d'$  decrement or a lesser  $\beta$  increment than their normal counterparts, they are said to exhibit a sustained attention deficit (Sergeant & van der Meere, 1990).

### ADHD and Sustained Attention

One of the most consistent findings in attention research is that ADHD children do poorly on tasks of sustained attention (Douglas & Peters, 1979; Sergeant & van der Meere, 1990). On the CPT, ADHD children repeatedly have been shown to make more omission and commission errors than control children. Using signal detection analysis, van der Meere and Sergeant (1988) found that ADHD children exhibited a constantly lower  $d'$ . Because  $d'$  is an index of arousal, these authors hypothesized that ADHD children may be chronically underaroused. O'Dougherty, Nuechterlein, and Drew (1984) concur with this finding but also cite evidence for a relatively lower  $\beta$ . Because  $\beta$  reflects effort as well as activation, a relatively lower  $\beta$  would seem to indicate constant problems either with impulse control or underactivation.

The hypothesis that ADHD children actually have a sustained attention deficit (that is, a greater impairment in performance over time than control children) has been more controversial. Schachar, Logan, Wachsmuth, and Chajczyk (1988), for example, compared ADHD children's performance to that of their

normal counterparts on each of three versions of the CPT. They found no evidence of a differential change in performance over time. Draeger, Prior, and Swanson (1986) likewise found no deficit in their study of ADHD performance on the CPT. By contrast, other studies have found ADHD children to have a greater sustained attention decrement than control children (Nuechterlein, 1983; Seidel & Joschko, 1990).

When a sustained attention deficit has been found in ADHD children, the problem thus far has been attributed to difficulty with  $\beta$  rather than  $d'$ . Van der Meere (1988) and Sergeant and van der Meere (1990) found that on tasks of sustained attention, normal children adopt a more rigid criterion for responding as they become more familiar with the target. ADHD children fail to make this adaptation. Nuechterlein (1983) examined differences in  $\beta$  across five versions of the CPT. He also found that ADHD children were less cautious in responding and that this effect was especially predominant in the first part of the task. Additional support for a problem with  $\beta$  comes from the fact that methylphenidate improves ADHD children's performance, so that the criterion for responding becomes more conservative (like control children) with time on task (Sergeant & van der Meere, 1990). Sonnevile (1991) similarly reports improvement in sustained attention with methylphenidate. A study by Seidel and Joschko (1990) is the only one to report a "borderline" significant deterioration in  $d'$  over time in ADHD relative to control children.

### Selective Attention

**Speeded classification task.** Selective attention is the process by which some aspects of a task are judged more relevant than others and are attended to preferentially (Douglas, 1983). The speeded classification task is a widely used measure of selective attention (Horn, Lorch, Lorch, & Culatta, 1985; Pelham, 1979; Strutt, Anderson, & Well, 1975). Throughout the task, stimuli are classified along a specified dimension. On Baseline trials, no other information is present; on Irrelevance trials, irrelevant stimuli are also present. The principal dependent measure is sorting time; errors are infrequent on this task. Slower sorting times on Irrelevance trials than on Baseline trials indicate interference by irrelevant stimuli (e.g., Lorch & Horn, 1986). If ADHD children experience more interference from irrelevant stimuli than nonreferred children, a selective attention deficit is indicated.

**ADHD and selective attention.** To date, there has been only one study that investigated the performance of ADHD children on the speeded classification task. Tarnowski, Prinz, and Nay (1986) found that these children sorted more slowly than control children but

were not more disrupted by the addition of irrelevant stimuli. Thus, ADHD children were found to be more inefficient on the speeded classification task but did not appear to have a selective attention deficit.

In a summary of the literature, Douglas (1983) agreed that ADHD children do not exhibit a uniform selective attention deficit. However, under certain conditions, such as when irrelevant stimuli were unusually appealing, ADHD children's performance do appear to suffer relative to normal children (Douglas, 1983; Landau, Lorch, & Milich, 1992). Ceci & Tishman (1984) attempted to address this discrepancy by proposing that ADHD children experience a "diffusion" of attention. That is, ADHD children spread their attention over both relevant and irrelevant stimuli. When processing demands are low, there are enough energy resources to complete the task without a decrement in performance. When processing demands increase, however, ADHD children are unable to reallocate resources necessary to process only relevant stimuli and their performance declines.

The present study seeks to resolve some of the contradictory findings concerning the role of sustained and selective attention in the deficits of ADHD children. To do this, a CPT and a speeded classification task were administered to groups of 7- to 12-year-old ADHD boys and their same-aged normal peers. Results were analyzed to determine whether there was evidence for sustained or selective attention deficits in ADHD boys.

## Method

### Subjects

The subjects for this study were 40 ADHD boys and a control group of 52 normal boys. All boys ranged in age from 7 to 12 years. ADHD boys were recruited from the University of Kentucky Hyperactive Children's Clinic and through an advertisement in the local newspaper. These boys met the accepted criteria for attention deficit hyperactivity disorder, including problems with attention, excessive motor movement, and impulsivity as listed in the third and revised edition of the Diagnostic and Statistical Manual of Mental Disorders (*DSM-III-R*; American Psychiatric Association, 1987). Normal boys were recruited from a local school system in Lexington, Kentucky. They were free of learning and behavior problems. Criteria for both the ADHD and normal boys were assessed by a combination of parent report on the mother version of the Conners Abbreviated Rating Scale (Goyette, Conners, & Ulrich, 1978; ADHD boys received scores  $\geq 15$ , normal boys received  $\leq 10$ ) and performance on the Peabody Picture Vocabulary Test-Revised (PPVT-R; Dunn & Dunn, 1981; all children had IQs  $\geq 80$ ). Additionally, clinic-referred ADHD boys had been pre-

viously assessed at the clinic on each of the *DSM-III-R* criteria. ADHD boys recruited from the newspaper met *DSM-III-R* criteria as measured by a parent report on the Disruptive Behavior Disorders Rating Form (Pelham, Gnagy, Greenslade, & Milich, 1992). Comparisons on demographic variables indicated that ADHD and control groups did not differ with regard to age ( $M_s = 120.7$  and  $121.6$  months),  $t(90) = .37, p > .05$ , or IQ ( $M_s = 106$  and  $110$ ),  $t(89) = 1.19, p > .05$ . As expected, the ADHD group was rated significantly higher on the mother version of the Conners Abbreviated Rating Scale ( $M_s = 18.2$  and  $5.5$ ),  $t(90) = 16.60, p < .001$ . ADHD boys obtained from the newspaper article did not differ significantly from those recruited from the hyperactivity clinic on the Conners Abbreviated Rating Scale ( $M_s = 18.7$  and  $18.1$ ),  $t(38) = .28, p = .78$ . The two groups also did not differ in age,  $t(38) = .88$ , or IQ,  $t(38) = .09$ . All subjects earned \$10 for their participation.

### Procedure

This study was conducted as part of a larger, ongoing research project on the television viewing of ADHD children at the University of Kentucky. Each child watched two television programs. The CPT and the speeded classification task were completed, in counterbalanced order, during the interval between the two programs. The PPVT-R was administered after each child finished watching the last television program. All ADHD children were medication-free on the day of the study.

**CPT.** For the CPT, a computer with color monitor was used. The basic program was developed by Lindgren and Lyons (1984). Presentation rate was fixed at 900 msec and the duration time was 100 msec. There were three blocks across time, each consisting of 300 letters including 30 target pairs. The child was told that he was to press the spacebar every time an orange H appeared immediately followed by a blue T. The experimenter then asked the child to repeat the instructions to insure understanding of the task. Then, a 45-sec practice trial was held. If the child made fewer than seven errors on this trial, the experimenter started the program. Otherwise, the experimenter repeated the instructions and the practice trial until fewer than seven errors were made. The program lasted 13 min, and at the end of this time both omission and commission errors were recorded across the three blocks of the task.

**Speeded classification task.** For the speeded classification task, there were three decks of twenty-four 10.2- $\times$ 7.6-cm cards—the Practice deck, the Baseline deck, and the Irrelevance deck. In the Practice deck, all cards contained a black outlined square on a white field. On half the cards, the square was 1.27 cm

on each side (small square) and on the other half the square was 1.9 cm on each side (large square). In the Baseline and Irrelevance decks, all of these cards had a 1.9- × 1.9-cm matrix of dots in the center of each card. Half of the cards in each deck had a 4 × 4 dot matrix and half had a 6 × 6 dot matrix. In the Baseline deck, the matrix was centered on a white background. In the Irrelevance deck, the matrix was surrounded either by an octagon or a cross and placed on either a yellow or a pink background. All possible combinations of matrix type, background color, and background form appeared equally across the 24 cards.

A trial consisted of the sorting of one deck of 24 cards. Each child completed nine trials. On the first trial, the child sorted the Practice deck, whereas the other eight trials were divided into four blocks of two. Each block contained one Baseline and one Irrelevance trial, with order of the Baseline and Irrelevance trials in each block randomly determined. The entire procedure lasted 15 to 20 min.

On the Practice trial, the child was instructed to put cards containing the small squares in one pile and cards containing the large squares in another pile. Sample cards showing each square size were placed in front of the child as a guide. For the Baseline and Irrelevance trials, similar instructions were given except the child was instructed this time to put the cards with the dots "closer together" in one pile and the cards with the dots "further apart" in the other pile. The child was told that sometimes things besides the dots would be on the card, but always to focus on the dots when sorting. Sample cards for all trials showed each type of dot matrix on a white background.

At the beginning of each trial, the appropriate deck was placed face down in front of the child. The child was instructed to use only one hand and to turn the cards over one at a time. Speed and accuracy were emphasized. Each trial began when the experimenter said "Go" and ended when the last card was placed on a pile. Sorting time and number of errors were recorded for each trial. Trials on which more than four errors were made were repeated. The reported data were from the final sort on any trial.

### Results

Analyses of variance were conducted on the CPT and speeded classification tasks to determine if subjects' performance on either task differed across time or group status. Age was also included as a variable. Throughout the analyses, group status (ADHD or normal) and age (7–9 years or 10–12 years) were between-subjects variables and time was a within-subjects variable. On the CPT, performance across time was divided into three blocks, and on the speeded classification task there were four sorting blocks across time. The speeded classifica-

tion task had an additional within-subjects variable of trial type (Irrelevance vs. Baseline).

Dependent variables on the CPT included the number of omission errors, number of commission errors, perceptual sensitivity ( $d'$ ) and decision criterion ( $\beta$ ). Performance on the speeded classification task was measured by the mean sorting time for the Irrelevance and Baseline decks.

### Performance on the CPT

Table 1 presents a summary of the mean number of omission and commission errors as well as the mean  $d'$  and  $\beta$  for both groups of children. For omission errors, there was a main effect for block,  $F(2, 180) = 16.73$ ,  $p = .000$ . A trend analysis indicated that the number of omission errors increased linearly with time,  $F(1, 90) = 26.92$ ,  $p < .000$ . The quadratic trend for this relation was nonsignificant,  $F(1, 90) = 2.73$ ,  $p > .05$ . The performance of both ADHD and control groups deteriorated with time on task,  $F(2, 78) = 12.57$ ,  $p < .000$ , and  $F(2, 102) = 3.15$ ,  $p < .05$ , respectively.

ADHD boys averaged significantly more omission errors ( $M = 8.2$ ) on the CPT than their normal counterparts ( $M = 5.3$ ),  $F(1, 90) = 7.03$ ,  $p < .01$ . There was a significant Group × Block interaction,  $F(2, 180) = 4.58$ ,  $p < .01$ , and a trend analysis indicated that ADHD boys' performance deteriorated linearly at a faster rate than control boys' performance,  $F(1, 90) = 6.70$ ,  $p < .01$ . There was no quadratic trend for this interaction,  $F(1, 90) = 1.66$ ,  $p > .05$ . Comparison of omission errors for the two groups during the first time period using Tukey's procedure yielded nonsignificant results,  $F(1, 80) = 1.12$ ,  $p > .05$ . However, by the third time period the ADHD boys were making significantly more omis-

Table 1. Measures of Performance on the CPT

Group	Performance Measure	Time Blocks		
		1	2	3
ADHD <sup>a</sup>	Omission errors	6.10	8.93	9.72
	SD	5.06	7.16	7.60
	Commission errors	23.05	24.30	25.15
	SD	36.61	41.60	37.38
	$d'$	2.59	2.23	2.14
	SD	1.04	1.13	1.25
	$\beta$	3.08	3.95	3.98
Control <sup>b</sup>	SD	2.89	3.62	3.37
	Omission Errors	4.65	5.39	5.87
	SD	3.95	5.21	5.96
	Commission Errors	10.29	11.04	11.27
	SD	17.03	20.25	22.68
	$d'$	3.10	3.07	3.01
	SD	0.89	1.05	1.13
$\beta$	4.02	4.49	4.27	
SD	3.24	3.68	3.24	

<sup>a</sup> $n = 40$ . <sup>b</sup> $n = 52$ .

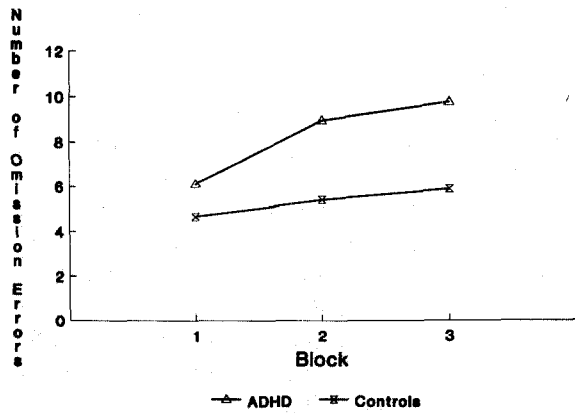


Figure 1. Number of omission errors for ADHD and control boys as a function of time.

sion errors,  $F(1, 80) = 4.6, p < .05$ . Figure 1 illustrates these results.

When examined by age, older children generally made fewer omission errors than younger children,  $F(1, 88) = 13.54, p < .01$ . However, there was no Group  $\times$  Age interaction,  $F(1, 88) = .35, p = .945$ , and no Age  $\times$  Block interaction,  $F(2, 176) = 2.44, p = .09$ .

For commission errors, there was a main effect of group,  $F(1, 90) = 4.91, p < .05$ . ADHD boys made more commission errors on the CPT ( $M = 24.16$ ) than control boys ( $M = 10.88$ ). There was no main effect of block,  $F(2, 180) = .61, p > .05$ , and no Group  $\times$  Block interaction,  $F(1, 90) = 1.58, p = .211$ . There was a trend for older children to make fewer commission errors than younger children,  $F(1, 88) = 3.62, p = .06$ . However, there was neither an Age  $\times$  Group nor an Age  $\times$  Block interaction,  $F(1, 88) = 0.11, p = .744$  and  $F(2, 176) = .22, p = .805$ , respectively.

For  $d'$ , there was a main effect for block,  $F(2, 180) = 7.92, p < .01$ . This effect was a linear decline according to a trend analysis,  $F(1, 90) = 13.12, p < .000$ . The quadratic trend was nonsignificant,  $F(1, 90) = 1.12, p > .05$ . Perceptual sensitivity also differed significantly between ADHD and control groups,  $F(1, 90) = 12.24, p < .01$ , with control boys ( $M = 3.06$ ) having a greater  $d'$  than ADHD boys ( $M = 2.32$ ). There was a significant Group  $\times$  Block interaction,  $F(2, 180) = 3.81, p < .05$ . Specifically, ADHD performance deteriorated linearly at a faster rate than control performance,  $F(1, 90) = 5.51, p < .05$ . Again, there was no significant quadratic trend,  $F(1, 90) = 1.58, p > .05$ .

When examined by group, ADHD boys' performance exhibited a linear decline over time,  $F(1, 39) = 16.51, p < .000$ . The quadratic trend was nonsignificant,  $F(1, 39) = 2.38, p = .13$ . Control boys' performance did not change significantly over time,  $F(2, 102) = .53, p > .05$ . Tukey's procedure indicated that during the first time period,  $d'$  differed significantly between ADHD and control groups,  $F(1, 80) = 3.78, p < .05$ . When examined by age, older children had a greater  $d'$  than younger children,  $F(1, 88) = 16.16, p < .01$ . However,

there was neither an Age  $\times$  Group nor an Age  $\times$  Block interaction,  $F(1, 88) = .41, p = .523$ ,  $F(2, 176) = .55, p = .578$ , respectively.

For decision criterion, B, there were no significant effects for block,  $F(2, 180) = 1.96, p > .05$ , group,  $F(1, 90) = 1.11, p > .05$ , or the Group  $\times$  Block interaction,  $F(2, 180) = .39, p > .05$ . There also were no significant effects of age,  $F(1, 88) = .01, p = .908$ .

### Performance on the Speeded Classification Task

Table 2 shows mean sorting times for Baseline and Irrelevance trials of the speeded classification task. Results indicated a main effect of block on sorting times,  $F(3, 270) = 29.90, p < .000$ . Trend analysis indicates that this effect was significant for both linear and quadratic components,  $F(1, 90) = 83.74, p < .000$ , and  $F(1, 90) = 6.11, p < .05$ . Specifically, sorting speed decreased over time, but the slope of this decrease was significantly greater at the beginning than in the later blocks of the task. There was no cubic trend for sorting speed over time,  $F(1, 90) = 2.55, p > .05$ .

There was also a main effect of trial type for all boys, such that the Irrelevance deck was sorted more slowly than the Baseline deck,  $F(1, 90) = 88.77, p < .000$ . Trial type and block interacted significantly,  $F(3, 270) = 9.85, p < .000$ , such that the effect of the irrelevant stimuli was greater in magnitude during early sorting trials and decreased with time. Again, the linear and quadratic components of this interaction were significant,  $F(1, 90) = 17.44, p < .01$ , and  $F(1, 90) = 8.20, p < .01$ , whereas the cubic relation was nonsignificant,  $F(1, 90) = 3.42, p > .05$ . Figure 2 illustrates these results.

Overall, the ADHD children ( $M = 53.34$ ) sorted significantly slower than control children ( $M = 46.42$ ),  $F(1, 90) = 10.66, p < .01$ . However, there was neither a Group  $\times$  Trial Type interaction,  $F(1, 90) = 1.28, p > .05$ , nor a Group  $\times$  Block interaction,  $F(3,$

Table 2. Mean Sorting Times for Baseline (A) and Irrelevance Decks (B) on the Speeded Classification Task

Group	Deck	Sorting Trial			
		1	2	3	4
ADHD <sup>a</sup>	A	53.98	51.73	50.70	48.90
	SD	10.57	16.23	15.03	11.73
	B	61.50	54.23	53.68	52.03
	SD	13.05	13.59	12.18	11.70
Control <sup>b</sup>	A	46.27	44.62	42.35	42.19
	SD	8.83	10.57	10.53	9.39
	B	55.64	48.29	46.15	45.87
	SD	13.32	12.25	9.48	11.26

<sup>a</sup> $n = 40$ . <sup>b</sup> $n = 52$ .

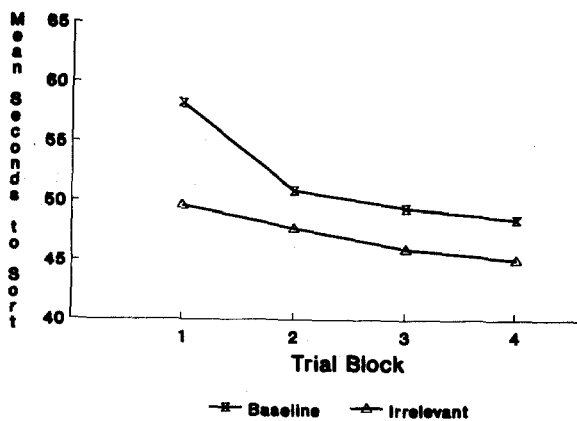


Figure 2. Mean sorting time for ADHD and control boys as a function of trial block.

270) < 10.36,  $p > .05$ .

Older children sorted faster than younger children,  $F(1, 88) = 31.88, p < .001$ . There was an Age  $\times$  Block interaction with the older children's sorting times improving more than the younger children over sorting blocks,  $F(3, 264) = 2.62, p = .05$ . There was neither an Age  $\times$  Group interaction nor an Age  $\times$  Trial Type interaction,  $F(1, 88) = 1.11, p = .296$  and  $F(1, 88) = .00, p = .950$ , respectively.

## Discussion

### Continuous Performance Test

Data from the CPT replicate findings in the literature that ADHD children make more omission and commission errors than their normal counterparts (Douglas & Peters, 1979; Sergeant & van der Meere, 1990). Older children generally made fewer errors than younger children, but this trend did not seem to be different across ADHD and control groups. The overall pattern of errors in each group varied with error type.

The groups did not differ significantly in the first time block with regard to omission errors. This suggests that, to begin with, ADHD boys were able to perform comparably to normal boys. Although the omission errors of both groups increased over time, ADHD boys showed a sharper increase than control children. Thus, even according to the strict criteria advocated by Sergeant and van der Meere (1990), the ADHD boys exhibited a sustained attention deficit.

With regard to commission errors, ADHD and control boys' performance did not change with time, although ADHD boys did make more commission errors overall. It is impossible to determine from these data whether this latter result reflects inattention to the task or problems with impulsivity on the part of the ADHD children. In the future, reaction time could be measured on the CPT, and commission errors thus could be

divided into fast (impulsive) and slow (inattentive) subtypes (Halperin et al., 1988; Sergeant & van der Meere, 1990).

When signal detection analysis was applied to the CPT, the increased number of errors found among the ADHD boys resulted in an overall lowered  $d'$ . Lowered  $d'$  levels for this group are not new in the literature (O'Dougherty et al., 1984). According to Sergeant and van der Meere (1990), perceptual sensitivity reflects general arousal level of an individual. The lowered  $d'$  levels in this study thus provide further evidence for Sergeant and van der Meere's (1990) assertion that ADHD boys are chronically underaroused.

When examined over time, however, ADHD children experienced a  $d'$  decrement, whereas control children's performance was constant. Sergeant and van der Meere (1990) contend that for a sustained attention deficit to be present, both groups' performance must change with time on task. They would interpret the results of this study to mean the control children's arousal resources were not sufficiently taxed so as to precipitate a  $d'$  decrement. Even though ADHD boys did experience a greater  $d'$  decrement over time, these results therefore would not be interpreted as conclusive evidence for a sustained attention deficit. However, such a stringent criterion for determining a sustained attention deficit is not universally shared (Seidel & Joschko, 1990).

These findings raise the more general question of why  $d'$  deteriorated over time in ADHD boys but not in normal boys. One possibility is that the difficulty in maintaining attention does not lie in an isolated deficit of an information processing pool but in the way effort modulates the arousal and activation pools (Sergeant & van der Meere, 1990). If energy resources were not available or were not being used optimally by ADHD boys, difficulties could arise with either the arousal or activation pools. For example, van der Meere and Sergeant (1988) proposed that a "compensatory" mechanism exists between activation and effort. When activation resources are taxed, a normal child compensates by using effort resources, and performance does not suffer. In the ADHD child, however, either the effort resources are not available or are not optimally utilized, and the child's performance declines. What looks like a child experiencing difficulties with activation is thus a child who is unable to use effort resources to compensate.

A similar mechanism could be in place for arousal resources. When a child's arousal resources are taxed, effort resources are used to compensate without a drop in performance. Again, if the compensatory mechanism is not available in ADHD children, a decline in performance would occur. This time, however, it would appear to be attributable to problems with the arousal pool. In the present study, ADHD children's  $d'$  declined with time on task whereas control children's  $d'$  was

maintained over time. Perhaps control children were able to utilize effort resources and compensate for the demands the task placed on sustained attention whereas ADHD children could not.

Although the present study obtained results for the ADHD boys consistent with a sustained attention deficit attributed to number of omission errors, other studies have not always produced such results (Sergeant & van der Meere, 1990). It is possible that task parameters account for these contradictory findings. Research has shown that on tasks of sustained attention, performance over time is a product of the processing demands of a task, the individual's sensitivity to the task stimuli, and the criterion set by the individual for a "yes" response (Parasuraman, 1984). When processing demands of a task are high, normal children experience a decrease in sensitivity to task stimuli over time and/or an increase in their criterion for making a "yes" response.

Surprisingly, little research has been conducted on the effects that CPT task parameters have on the performance of ADHD children. Seidel and Joschko (1990) hypothesized that if parameters such as event rate, display time, signal density, preparation, and length of task were systematically studied, many of the inconsistent results in the literature could be resolved. Sergeant and van der Meere (1990) made a similar prediction. Indeed, examination of several studies seems to indicate that the selection of parameters on the CPT is a somewhat arbitrary task. Parameters, if reported at all, vary widely from study to study. For example, in a review of present CPT literature, event rate varied between 730 and 4000 msec, whereas display time varied between 100 and 650 msec (Chee, Logan, Schachar, Lindsay, & Wachsmuth, 1989; Klee & Garfinkel, 1983; Sosteck, Buchsbaum, & Rapoport, 1980; Tarnowski et al., 1986).

In the present study, the event rate was 900 msec and display time was 100 msec. Both of these are relatively brief as compared to the parameters used in the CPT studies mentioned above. Parasuraman (1984) noted that at fast event rates and short display times, perceptual sensitivity decreased in tasks of sustained attention. Thus, the task parameters in this study may have placed demands on the encoding and/or arousal stages of information processing for which ADHD children were not able to compensate and which resulted in a sustained attention deficit when omission errors were examined.

### Speeded Classification Task

Results of the speeded classification task indicate that sorting time increased significantly for ADHD and control boys as a function of the addition of irrelevant stimuli. This suggests the task placed demands upon selective attention for all children. Older children

sorted faster than younger children, but again there was no Group  $\times$  Age interaction. Performance on the speeded classification task was also measured over time. In general, interference from irrelevant stimuli decreased as time on task increased, possibly due to habituation of responses to the irrelevant stimuli (Lorch & Horn, 1986). Improvements in overall sorting times also occurred with practice. Results of this study match those of Tarnowski et al. (1986) and indicate that ADHD boys were slower on the speeded classification task but appeared no more distracted than normal boys by the irrelevant stimuli. That is, ADHD boys did not exhibit a selective attention deficit. When performance was examined over time, ADHD boys did not appear to have any more difficulty than normal boys in habituating to irrelevant stimuli or in improving sorting time with practice.

The absence of a selective attention deficit does not directly support Ceci and Tishman's (1984) contention that ADHD children have "diffuse" attention, but it does not preclude this hypothesis either. These authors note that a selective attention deficit results only when the processing demands of the task are high. If the diffusion hypothesis is correct, the results of this study suggest that the presence of irrelevant stimuli in this speeded classification task may not place enough processing demands on ADHD children to elicit a selective attention deficit.

Because ADHD boys did not exhibit a deficit in performance on the speeded classification task, the memory selection and decision-making stages that have been previously implicated in selective attention do not seem problematic here (Johnston & Dark, 1983). ADHD boys did, however, exhibit a general inefficiency throughout the speeded classification task. This finding would imply problems elsewhere in processing stages or energy pools. Because problems with arousal and/or activation have already been implicated in the CPT performance of the ADHD boys, it would be reasonable to assume that one of these could also be involved in their inefficient performance on the speeded classification task. A second possibility is that effort could be directly affecting the decision-making stage of processing (Sanders, 1983). If the diffusion hypothesis is true, ADHD children would spread effort resources over all stimuli. At low task demands, perhaps like those in the present speeded classification task, enough resources would be available, so a decision would take longer but no performance deficit would occur. At high task demands, attention might become so diffuse that ADHD children would lack effort resources to perform comparably to normal children.

Several limitations of the present study should be acknowledged. First, reaction time on the CPT should be measured. In this way commission errors could be divided into fast (impulsive) and slow (inattentive)

subtypes (Halperin et al., 1988; Sergeant & van der Meere, 1990). Second, the effect of task parameters on performance in both ADHD and control groups needs to be examined. It is possible that the failure to control task parameters has accounted for the mixed findings on sustained attention in the research to date. One hypothesis is that ADHD children experience a sustained attention deficit only when task parameters place large demands on information processing resources. Third, the present study does not differentiate between ADHD children with and without concomitant aggression. Halperin et al. (1990), using a modified version of the CPT, found that the pure hyperactive group tended to make errors associated with problems in inattention, whereas the hyperactive and aggressive children tended to make errors associated with impulsivity.

In summary, the ADHD boys performed more poorly than the control boys on both tasks. They were slower on the speeded classification task and they made more omission and commission errors on the CPT. Taken together, this could be due to a general lack of resources, perhaps in the effort pool. Several studies have found that ADHD children are deficient in exerting sufficient effort on tasks (Douglas, 1983). Alternatively, these children may be inefficient in allocating resources, so that they do more poorly as task demands increase.

Findings of the present study constitute evidence for a sustained attention deficit among ADHD boys but no evidence for a selective attention deficit. Consistent across both tasks was a general inefficiency of the ADHD boys, which may reflect either insufficient effort resources or inappropriate allocation of these resources. Systematic investigation of task parameters in future research may resolve contradictory findings regarding sustained and selective attention deficits among ADHD children.

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# Investigation of a Direct Intervention for Improving Attention in Young Children With ADHD

Kimberly A. Kerns

*University of Victoria  
Victoria, British Columbia*

Karen Eso

*Bakersfield College, CA*

Jennifer Thomson

*University of Washington*

The efficacy of a new set of child-oriented direct intervention materials, *Pay Attention!* (1994), was investigated in 14 children, ages 7 to 11 years, diagnosed with attention deficit hyperactivity disorder (ADHD). Treatment and control groups were matched for age, sex, and medication status. Both groups completed pre- and posttraining assessment batteries that included psychometric measures of attention, a measure of academic efficiency, and behavioral rating scales completed by parents and teachers. Results indicate that children who received the direct intervention did significantly better on a number of nontrained measures of attention and academic efficiency. Behavioral ratings of inattention–impulsivity and hyperactivity completed by parents did not differ following treatment, although a marginally significant improvement in inattention–impulsivity was noted by school teachers. These results suggest that direct interventions aimed at improving attention may be a valuable treatment option for improving cognitive efficiency in children with ADHD and warrant further investigation.

Attention deficit hyperactivity disorder (ADHD) is the one of the most prevalent childhood disorders, with estimates ranging from as many as 3 to 5% of all children being affected (Pennington, 1991; Szatmari, 1992). Current clinical consensus is

that the primary deficits seen in ADHD are those of inattention and impulsive–hyperactive behavior (American Psychiatric Association, 1994). Deficits in these areas commonly arise during the preschool or early childhood years, are significantly inappropriate for the child’s developmental level, and appear to be relatively stable and persistent over time (Mannuzza, Gittelman-Klein, Bessler, Malloy, & LaPadula, 1993; Weiss & Hechtman, 1993). Considerable controversy exists regarding the nature of the core ADHD deficits and whether children with inattention alone differ fundamentally from those with accompanying hyperactivity–impulsivity symptomatology. Despite these controversies, it is clear that the majority of children who have ADHD have basic deficits in the areas of behavioral inhibition and ability to sustain attention to tasks over time (Barkley, 1997b; Pennington, 1991).

Attention is not a unitary construct, and there are several models proposed to outline the major components of attention and their underlying neurological structures (Kerns & Mateer, 1996; Mirsky, Anthony, Duncan, Ahearn, & Kellam, 1991; Posner & Peterson, 1990; Sturm, Willmes, Orgass, & Hartje, 1997). Regardless of which model is adopted, most include separable components of attention, such as the ability to sustain attention over time (vigilance), the ability to attend to stimuli selectively, the ability to alternate or switch attention stimuli or tasks, and the ability to divide attention so as to maintain more than one ongoing process. Sohlberg and Mateer (1989a) suggested that attention is hierarchical. Their model suggests that the lower levels of attention include such basic functions as being able to focus attention (with no competing stimuli) and sustain attention over time. Higher levels of attention, such as being able to alternate attention quickly between tasks or to divide attention to be able to do more than one task at a time, require that lower levels of attention are intact. These higher order aspects of attention are hypothesized not only to be dependent on these underlying skills but also to involve the ability to disengage attention and to inhibit responding. Such aspects of attention are dependent on the frontal regions of the brain and begin to overlap with some of the abilities that have been termed *executive functions*.

Research suggests that children with ADHD have a primary deficit in the ability to sustain attention over time (Douglas, 1983; Hooks, Milich, & Lorch, 1994; Prinz, Tarnowski, & Nay, 1984; Seidel & Joschko, 1990; van der Meere & Sergeant, 1988). It is less clear whether children with ADHD have specific difficulty with selective attention, a more complex behavior requiring the ability to preferentially attend to relevant aspects of a task while ignoring irrelevant information. Although some studies have failed to find deficits in selective attention in children with ADHD (Hooks et al., 1994; Lorys, Hynd, & Lahey, 1990; Trommer, Hoepfner, Lorber, & Armstrong, 1988), others have argued that there is evidence for a selective attention deficit in this group (Ceci & Tishman, 1984; Landau, Lorch, & Milich, 1992). For example, children with ADHD are known to have significant difficulty on tasks such as the Stroop Color and Word Test

(Golden, 1978) and cancellation tasks that have been described as measures of selective attention (Barkley, Grodzinsky, & DuPaul, 1992). It may be that children with ADHD have particular difficulty with tasks of selective attention when they have a salient prepotent response to items that are not to be attended to or to be "ignored." Children with ADHD may fail to inhibit response to such stimuli. There is less known about alternating and divided attention in children with ADHD, although deficits seen on tasks such as the Wisconsin Card Sorting Test (Heaton, Chelunc, Talley, Kay, & Curtiss, 1993) suggest that they do have difficulty in these areas as well.

Given the high prevalence of ADHD and its impact on many aspects of development, considerable effort has been focused on various treatments to alleviate symptoms. Although pharmacological management has emerged as a primary mode of treatment, stimulants typically do not ameliorate all the problems these children experience, and they often continue to have some difficulty with attentive behavior. As such, the use of nonpharmacological treatments that are designed to improve attention and other cognitive abilities have been investigated.

Interventions for cognitive deficits generally fall into one of three realms (Mateer, Kerns, & Eso, 1996): (a) environmental interventions that provide contextual support in the area of impaired ability (e.g., audio taping books for individuals with reading disabilities), (b) interventions aimed at compensating for the deficit in ability (e.g., use of memory notebooks or watches with alarms for an individual with memory impairment), and (c) the use of direct interventions aimed at improving the underlying cognitive process and eliminating or reducing the deficit itself. In children with ADHD, environmental interventions to improve attention have included a variety of alerting and reward systems to increase attention to the task. Compensatory approaches have included the use of metacognitive strategy training, in which children are taught reflective problem-solving strategies and self-control skills (see review by [Abikoff, 1991](#)). The use of direct process-specific interventions to improve attention has had almost no investigation in the ADHD literature, although this type of intervention has frequently been utilized in the field of cognitive rehabilitation for individuals who have sustained acquired brain injuries (see Mateer & Mapou, 1996 for a review).

The premise of direct intervention or process-specific approaches, as applied to the treatment of attentional impairments, is that attentional abilities can be improved by providing structured opportunities for exercising particular aspects of attention. Treatments have usually involved having participants engage in a series of repetitive drills or exercises that are designed to provide opportunities for practice on tasks with increasingly greater attentional demands. Repeated activation and stimulation of attentional systems are hypothesized to facilitate changes in cognitive capacity that presumably reflect underlying changes in neuronal activity. Effects of training can be measured at several levels, including (a) changes in training task performance, (b) changes in performance on untrained psychometric

measures of attention, and (c) changes in aspects of daily function dependent on attentional capacity.

## STUDIES OF ATTENTION TRAINING IN ADULTS

Changes in performance on attention training tasks over time have, not surprisingly, been quite consistently shown in adult samples. Even in individuals with severe acquired cognitive impairment, improvements have been shown on tasks involving sustained attention to task, accuracy and speed of visual search, and a wide range of tasks requiring increasingly complex stimulus–response demands (Ben-Yishay, Piasetsky, & Rattock, 1987; Diller et al., 1974; Wood & Fussey, 1987). More impressive, a large number of studies have shown positive effects of attention training on unpracticed psychometric measures (Ethier, Braun, & Baribeau, 1989; Finlayson, Alfano, & Sullivan, 1987; Gray & Robertson, 1989; Gray, Robertson, Pentland, & Anderson, 1992; Sohlberg & Mateer, 1987). Although some of these investigations focused on only one aspect of attention, others addressed multiple levels of attention, including sustained attention, selective attention, and divided attention. In a recent study (Sturm et al., 1997), the issue of training specificity with regard to different components of attention was addressed. Sturm et al. reported that sustained attention training resulted in improvements on both an untrained measure of sustained attention and on a measure of more complex attention. However, training at the more complex level alone was not as effective and in some cases was even deleterious. These findings are consistent with recent evidence supporting separable neuroanatomical circuits for sustained attention, selective attention, working memory, and inhibitory control (Mirsky et al., 1991; Posner & Peterson, 1990).

Despite promising results from these investigations, there have been concerns regarding the generalizability of improvements in attention to everyday or functional activities. Although this remains an area in need of further study, there has been some experimental support for a positive impact of attention training on reading ability (Raskin & Mateer, 1993; Wilson & Robertson, 1992), driving (Sivak et al., 1984), everyday memory ability (Mateer & Sohlberg, 1988), and work performance (Mateer, Sohlberg, & Yougman, 1990). Complicating interpretation of these findings, however, is the fact that most of these interventions involved not just attention training exercises but also activities and interventions designed to facilitate awareness, emotional response to attentional slips, and self-regulatory skills.

Although the mechanisms underlying a change in attentional performance–capacity remain unknown, a number of studies have demonstrated changes in the electrophysiological response of the brain during attentional tasks. A series of evoked potential studies using attention sensitive measures have demonstrated a “normalization” of brain electrical response after attention training (Baribeau, Ethier, & Braun, 1989; Raskin, 1998).

## STUDIES OF ATTENTION TRAINING IN CHILDREN

There are fewer studies that have examined the efficacy of direct intervention, also known as *process-specific approaches*, in children with attention disorders. Two of these studies examined attention training effects in older children and adolescents who demonstrated acquired impairments in attention secondary to traumatic brain injury (Thomson, 1995; Thomson & Kerns, in press), and two focused on attention training effects in children with the developmental attention deficits seen in ADHD (Semrud-Clikeman, Harrington, Clinton, Connor, & Sylvester, 1998; Semrud-Clikeman et al., in press; [Williams, 1989](#)).

Thomson (1995) examined the efficacy of attention training in six adolescents (ages 14–17 years) who had sustained moderate to severe head injury in the previous year. The participants were seen three times weekly in ½-hr sessions for a total of 12 weeks. Training materials were all from the Attention Process Training (APT) system developed for adults by Sohlberg and Mateer (1989b). A single case design relying on multiple baselines across measures was utilized. Results revealed a systematic improvement in attention abilities (as measured through a sustained attention task) as well as in reading speed and performance on a timed mathematics measure. General intellectual functioning and visual-perceptual abilities did not improve, demonstrating the specificity of the intervention to attention. No change was seen on parent or teacher ratings scales of inattentive or hyperactive behavior. Thomson and Kerns (in press) described significant improvements following attention training in two other school-age children who had suffered mild traumatic brain injuries. Gains were seen primarily on tasks of attention and in some cases on tasks of executive function and memory. No gains were noted in general abilities.

[Williams \(1989\)](#) examined the effectiveness of attention training in six children (ages 8–13 years) who were diagnosed with ADHD. He also utilized attention training materials from the APT for adults. Children were trained in two groups, and training took place for 2 hr per day, 4 days per week, over a period of 5 weeks during the summer break. Williams evaluated changes in performance on training tasks, as well as pre- and posttreatment changes in independent measures of attention, academic efficiency, and parent-reported measures of attention. His results revealed significant improvements on the training materials and on independent measures of attention, with some gains on academic efficiency measures (although not enough to reach statistical significance). There were no changes reported in parental report of attention abilities.

Semrud-Clikeman and colleagues (Semrud-Clikeman et al., 1998; Semrud-Clikeman et al., in press) examined the efficacy of APT training coupled with training in problem solving within a school setting. Children were selected by teachers as having problems in attention and completing work. Using a multimodal and multi-informant assessment, children were assessed as either having difficulty

in this area or not and divided into one of three groups: ADHD children who would receive the intervention, ADHD controls who would receive no intervention, and normative control children with no attention problems. Children with poor attention skills identified in this manner had poorer performance on a visual and auditory attention task, measures of visual–motor ability, and cognitive flexibility. Children in the intervention group were administered tasks from the APT materials and also taught problem-solving strategies in small groups (5–7 children). Children were seen for 1 hr, twice weekly, for a period of 18 weeks. Pre- and posttesting revealed significant changes on a measure of visual cancellation and a measure of auditory attention. On the visual cancellation task, the ADHD group receiving treatment performed more poorly than the normal controls prior to treatment but did not differ from them following treatment. On the test of auditory attention, there was a significant improvement in the performance of the treated ADHD children following intervention, but there was no change in the ADHD controls. The authors commented informally that children off medications appeared to make better gains than those on medication during the treatment. Additionally, qualitative interviews with teachers revealed that children who had undergone the treatment seemed more attentive and showed improvement in completing tasks in class.

Due to the challenge of undertaking clinical efficacy trials, studies have often relied on single-case design methodologies or, when based on group designs, have small sample sizes and frequently no control condition. Only in the study by Semrud-Clikeman and colleagues (Semrud-Clikeman et al., 1998; Semrud-Clikeman et al., in press) was there a control group of children who were not receiving APT treatment. Even in that study, there was no true nonspecific treatment control group, as ADHD controls were simply not seen other than for pre- and posttesting. There have also been differences across these studies in delivery of treatment. Children participated in attention training either individually in some studies or in a group format in others. Some studies combined the attention training with other interventions, such as problem solving or awareness training, whereas others did not.

Overall, results of these studies utilizing direct intervention (a process-specific approach) appeared to be most encouraging for the older children. Perhaps this is not unexpected, given that the APT materials used in each of the studies were developed for use with adults. Many of the APT tasks rely on knowledge, skills, and concepts that are well established in adults but not in younger children. When used with younger children, many of the APT tasks involving alphabetizing, ordering operations, number manipulations, and mathematical operations needed to be significantly altered or eliminated altogether (Mateer et al., 1996).

This study was designed to build on and expand the work of Williams (1989) and Semrud-Clikeman et al. (in press) by evaluating the effectiveness of a new attention training program that was specifically designed for use with younger children (targeting ages 5–10 years) in an ADHD sample. The attention training

materials utilized were designed by Thomson, Seidenstrang, Kerns, Sohlberg, and Mateer (1994) and called *Pay Attention!* The materials are modeled after the APT materials designed by Sohlberg and Mateer (1989b) for adults. The materials are based on the same hierarchical model of attention, which includes sustained, selective, alternating, and divided attention. In an attempt to make the materials more interesting and engaging to young children, they are more colorful and visually interesting, and they focus on familiar concepts such as features of people (e.g., hair color, sex, clothing), family relationships (e.g., siblings, parents, grandparents), and the familiarity of household characteristics (e.g., the purpose of rooms). Other familiar constructs include the concepts of same and different, relative size, comparisons of visual features, and basic counting. As in the APT, both visual and auditory stimuli are used. Treatment tasks are graded in difficulty, and participants' performance on tasks relative to criterion is used as the basis for moving ahead or branching into more difficult tasks.

## METHOD

### Participants

Participants were recruited through advertisements distributed to professionals working in the greater Victoria area. Included in this distribution were pediatricians, pediatric psychiatrists and neurologists, the local children's hospital, mental health centers, and two school districts. To participate in the study, participants must have received a diagnosis of ADHD from a qualified medical practitioner and been under 12 years of age at the start of the study. Participants were screened to rule out (a) a history of any acquired central nervous system injury or dysfunction such as head injury, (b) any developmental disorder other than ADHD, and (c) diminished intellectual capacity (Kaufman Brief Intelligence Test [K-BIT] IQ < 80; Kaufman & Kaufman, 1990).

The treatment group included seven children matched by age (within 1 year) to seven children with ADHD assigned to the control group. The two groups were also matched for sex and medication status. There were four boys and three girls in each group, and five of the seven children in each group were on stimulant medications throughout the duration of the study (including pre- and posttreatment assessments). The average length of time since diagnosis was 30.17 months (range = 11–53 months). The majority of participants had been diagnosed by a pediatrician (75%), approximately 17% had received the diagnosis from a child psychiatrist, and the remaining 8% had been diagnosed by a pediatric neurologist. Specific initial diagnostic information was not available, but scores from parent rating scales suggested that all participants would fit the category of ADHD combined type. There were no significant differences between the experimental and control



groups on sex, diagnostic information, or medication status. The treatment group had a mean age of 9.39 years (range = 7–11 years); the mean age of the control group was 9.35 years (range = 7–11 years), with an average age difference between matched pairs of 4.57 months (range = 1–10 months).

## Measures

Pre- and posttreatment measures were administered prior to beginning the intervention and within 2 weeks of completing the treatment. Seven measures appropriate for young children (ages 5–12, the proposed age range for the study) were chosen. It was hypothesized that children in the treatment group would demonstrate improved scores on the six measures considered to be sensitive to attentional and executive function ability but make no improvement on a task of visual–spatial ability. In addition, performance on a measure of academic efficiency and both teacher and parent reports on behavioral rating questionnaires were obtained pre- and posttreatment.

Psychometric measures included the Coding, Digit Span, and Mazes subtests of the Wechsler Intelligence Scale for Children (3rd ed.; WISC–III; Wechsler, 1991). These measures were chosen because they are frequently used measures of freedom from distractibility (attention) and planning (executive function). The Attentional Capacity Test (ACT; Weber & Segalowitz, 1990) was utilized as a measure of sustained auditory attention. This test, which is presented on audiotape, requires that the child listen to strings of numbers and mentally count the numbers of targets. There are eight levels of the task that increase in difficulty; early levels require recognition of single targets, whereas higher levels require recognition of multiple targets or targets in particular relations.

Several tasks assessing sustained visual attention were utilized including subtests 2, 4, and 14 from the Underlining Task (Doehring, 1968; Rourke, Fisk, & Strang, 1986). This paper-and-pencil task is a cancellation-type task that requires the child to cross out as many target stimuli as possible in 60 sec. Subtest 14 (Boxes condition) of this task requires participants to underline every stimulus (all boxes) as quickly as possible and provides a measure of motor speed and sustained attention with no “target” or selective attention component. Subtests 2 and 4 (Selective Shapes condition) requires participants to only underline target crosses and diamonds, presented in the presence of more frequent nontarget stimuli and thus requiring more selective attention. For the purposes of this study, Subtest 14 was analyzed separately, and the scores of the two selective attention tasks were summed. A newly developed, computerized continuous performance test for preschool and young children was also used a measure of sustained visual attention. The Children’s Continuous Performance Task (CCPT; Kerns & Rondeau, 1998) presents pictures of animals paired with their sounds via computer and requires

that the child respond to pictures of a target animal (e.g., sheep). Scores include the number of correct hits and commissions.

The Matching Familiar Figures Test (MFFT; [Kagan, 1966](#)) was used as a measure of impulsivity and executive function. In this task, a picture of a familiar object, a set of highly similar variants, and one exact match are presented. Children are to point to the exact matching picture, and, if their choice is incorrect, they are allowed to try again (up to five tries). The mean time to first response across items (mean latency) and number of items correctly answered on the first attempt were recorded. The Day–Night Stroop Test ([Gerstadt, Hong, & Diamond, 1994](#)) was chosen as a measure of behavioral inhibition, executive function, and selective attention. This task, designed by Gerstadt et al., is modeled after the traditional Stroop Color and Word Test ([Golden, 1978](#)) but is thought to be more appropriate for young children, as it does not require the ability to read (and changes in reading ability across this age range might alter performance). Participants are asked to say *day* whenever a black card with a moon and stars is presented and to say *night* when a white card with a sun is presented. Children are required to respond as quickly as possible and, if they make an error, they are told to correct their response. The score reflects the amount of time required to complete 32 test cards.

Finally, the Hooper Visual Organization Test (VOT; [Hooper, 1983](#)), a measure of visual–spatial ability, was given to analyze the specificity of treatment effects. In this task, participants see a series of pictures of line drawings of objects that have been cut into pieces and rearranged in puzzle-like fashion. The participant must determine what the pictured objects are, and the score is based on the number of correct recognitions of the items.

As a measure of academic efficiency, participants completed sheets of age- and grade-appropriate arithmetic problems selected from curriculum workbooks. Pre- and posttest forms were different and were randomly assigned. The children were asked to complete as many problems as possible within a set time period, and the score reflected the number of problems completed correctly. Although neither overall academic performance nor academic achievement levels were hypothesized to change as a result of the intervention, it was thought that academic efficiency on grade-appropriate tasks might improve if children were better able to attend to the task.

Both parents and teachers completed the Attention Deficit Disorder Evaluation Scale (ADDES) Home and School versions ([McCarney, 1989](#)). One of each participant's parents (the child's mother in all cases) and the child's teacher completed this rating scale pre- and posttreatment. Scores were obtained for each of three scales—inattention, impulsivity, and hyperactivity. Because it was predicted that the *Pay Attention!* treatment would affect attentional skills and impulsive behavior but not hyperactivity, the inattention and impulsivity scales were averaged. Although both parents and teachers were aware that the children were enrolled in a study, they were blind as to whether the child was in the treatment or control group.

## Intervention

Participants in both the treatment and control groups were seen individually, twice weekly, for 30-min sessions over a period of 8 weeks. All children were assessed and seen for treatment by one of the investigators who also completed the pre- and posttesting. Parents and teachers in both groups were informed that the treatment involved working with a number of materials that were game-like for children and might include some computer tasks and audiotaped materials.

*Treatment group.* Participants in this group spent all of their sessions working with the *Pay Attention!* materials. This set of materials was designed to train different levels of attention, including sustained, selective, alternating, and divided attention in young children and includes both visual and auditory activities. All of the visually based activities involve a common set of stimuli that include drawings of children and adults in family constellations on playing cards. Individual characters can be distinguished by age (children, parents, grandparents), sex, hair color (e.g., blond, brown, black), and apparel (e.g., wearing a hat or not, wearing glasses or not). Stimulus sets are built on the premise of several families, each named by a color (e.g., the Blue, Green, and Black families) and identified by that color border on the cards. Each family also has a large plasticized picture of the layout of its home showing different rooms with objects. These homes can be used as locations for sorting tasks and, because they can be written on and erased, can also be used for searching for objects. Sample stimuli and brief descriptions of sample treatment activities are presented in the Appendix (see also Figures A1 and A2).

Activities involve responding to stimulus features and to relations among stimuli. For example, early on children may be required to complete tasks like “As quickly as you can, sort the cards so that all of the families are in different stacks.” As children progress with the materials, the tasks become more difficult and may include conditions, such as “As quickly as you can, sort the cards into stacks of boys versus girls, and put all the cards with someone wearing a hat upside down.” Auditory tasks are all presented on tape and start with simple tasks such as pressing a buzzer for a simple target word (e.g., “Buzz whenever you hear the word *ball*”). These tasks become progressively more difficult (e.g., “Buzz whenever you hear the name of something you might see in the sky”). Tasks are paced and become faster, or include distracting background sounds, or both as participants work through the hierarchy (for examples of auditory tasks, see Appendix). Children were not taught any specific strategies for improving performance, nor was any mention made of changing their approach to completing tasks outside of treatment sessions.

Sessions were conducted after school either in a small room in the school building or in our laboratory space. All children started at the basic level with tasks that required only sustained attention and progressed to more difficult tasks. These

were introduced as the child achieved criterion on simpler tasks (e.g., a 20% gain in speed while maintaining  $\geq 90\%$  accuracy on timed tasks or  $> 85\%$  accuracy on taped materials). Not all participants progressed through all the materials, as children progressed at different rates. Changes in performance on tasks were charted with the children as they performed them and, at the end of each treatment session, they selected a small toy prize for participating that day.

*Control group.* Sessions were again conducted after school, either in a small room in the school building or in our laboratory space. During their sessions, participants in this group engaged in a variety of computer-based activities, including puzzles and games such as *Freddi Fish* (1995), *Memory Castle* (1984), and *Math Blaster* (1992). Children only received social praise and the regular feedback provided by each of these activities. At the end of each session, however, children were able to select from the same box of small toy prizes as the children in the treatment group did for coming and participating in the activities.

## Data Analysis

The data from pre- and posttreatment testing were analyzed. Raw scores were used for all measures versus standardized scores for a number of reasons. First, given the number of measures used and the diversity of the age ranges of the normative data for these measures, some children would have remained in the same “normative group” for the duration of the study on some instruments and not on others. Because control children were not matched by age exactly, depending on birth dates, not all participants in the experimental and control groups would have had the same “norm changes.” Second, of interest in this investigation was the actual improvement made by the participants (not in comparison to some normative sample). Raw scores were felt to be more sensitive than standard scores because they provide the actual change from the participants’ previous performance versus the change in their performance relative to some standardization sample. Finally, all analyses involved examining changes within participants (pretreatment scores serving as the control); because groups were matched for age, sex, and medication status, there was no concern that these variables would be causally linked to changes in raw scores.

Data were submitted to an analysis of covariance (ANCOVA) procedure, analyzing group differences in posttest performance using the pretest score as a covariate. The assumption of homogeneity of slopes for ANCOVA was tested by including a term for the interaction between pretest score and group in the general linear model. This ANCOVA approach essentially analyzes group differences on the posttest after correcting for individual differences on the pretest. This procedure was preferred over a difference score analysis (i.e., posttest–pretest) because a traditional difference score is essentially the same procedure except that it restricts the beta weight of the covariate to 1 (Judd & McClelland, 1989). Addi-

tionally, difference scores do not clarify whether the group effect is due to the pre- or posttest. If the homogeneity of slopes assumption was met and a significant effect of treatment was found in the ANCOVA (indicating that the pattern of change between pre- and posttest was different for the two groups), then individual paired *t* tests for both groups were utilized to determine how much change each group exhibited and if that change was significantly different from zero.

## RESULTS

Comparisons between the treatment and control groups on pretest measures did not reveal any significant differences in IQ or in performance on standardized tasks of attention. The groups were equivalent in K-BIT IQ, WISC-III Digit Span, Coding, and Mazes. Standardized scores on all subscales of the ADDES and ACT and average latency to respond on the MFFT were also equivalent between the two groups for both parent and teacher reports. Table 1 provides means and standard deviations for both groups on each of these variables. Although as a group neither control nor experimental participants were impaired on these measures, all participants had at least one task in which they performed below expected levels given their intellectual ability.

Analyses of performance data following the intervention revealed significant treatment (group) effects on a number of the measures. A significant treatment effect,  $F(1, 13) = 9.55, p = .010$ , was found on the WISC-III Mazes subtest. Individual

TABLE 1  
Means and Standard Deviations by Group for Standardized Pretreatment Measures

Task	Experimental Group		Control Group		T Score <sup>a</sup>
	M	SD	M	SD	
K-BIT Total IQ <sup>b</sup>	110.00	13.30	108.14	6.18	-.34
WISC-III Coding subtest <sup>c</sup>	9.43	2.76	8.57	1.99	-.67
WISC-III Digit Span subtest <sup>c</sup>	9.57	2.51	7.14	2.85	-1.69
WISC-III Mazes subtest <sup>c</sup>	9.71	1.98	8.43	1.51	-1.37
Attentional Capacity Test <sup>c</sup>	8.90	2.65	7.35	3.85	-.83
ADDES Home Inattention <sup>c</sup>	4.00	2.97	3.86	3.07	-.09
ADDES Home Impulsivity <sup>c</sup>	3.17	2.86	3.86	2.11	.50
ADDES Home Hyperactivity <sup>c</sup>	2.50	2.43	2.57	3.26	.04
ADDES School Inattention <sup>c</sup>	6.50	2.07	6.71	2.69	.16
ADDES School Impulsivity <sup>c</sup>	6.00	3.16	6.14	3.02	.08
ADDES School Hyperactivity <sup>c</sup>	6.17	3.49	6.14	3.02	-.01

Note. K-BIT = Kaufman Brief Intelligence Test; WISC-III = Wechsler Intelligence Scale for Children (3rd ed.); ADDES = Attention Deficit Disorder Evaluation Scale.

<sup>a</sup>*T* is the *t* value for the differences between the groups on measures prior to treatment. <sup>b</sup>Scores are expressed in IQ scores ( $M = 100, SD = 15$ ). <sup>c</sup>Scores are expressed in scaled scores ( $M = 10, SD = 3$ ).

paired  $t$  tests revealed that only the treated group showed a significant improvement,  $t(6) = -2.50, p = .047$ . The effect of treatment was also significant on the ACT,  $F(1, 13) = 32.05, p = .000$ , again with only the treated group showing a significant improvement,  $t(6) = -12.73, p = .000$ . On the Underlining Test Boxes condition, the assumption of homogeneity of slopes was not met, suggesting that the effect of treatment varied depending on the pretest scores. There was a significant change (improvement) in performance,  $t(6) = -5.06, p = .002$ , in the treatment group but no reliable change in the control group (see Figure 1). In analyzing the Selective Shapes condition of this task, it was important to determine if there were changes above and beyond that due to improvement in just the sustained attention component assessed by the Boxes condition. Additional analyses were conducted using both the pretest scores for the Selective Shapes underlining condition (selective attention) and the change in performance on the Boxes underlining condition (sustained attention) score as covariates. This analysis determines the additional improvement for the selective attention component over and above that seen in the sustained attention component. These analyses revealed significant covariate effects on both the Selective Shapes condition pretest score and improvement in the Boxes condition, as well as an improvement in the selective attention component due to treatment,  $F(1, 12) = 8.62, p = .015$ . Again, only the treatment group had a significant change in performance (again an increase),  $t(6) = -7.69, p = .000$ . Figure 2 displays the mean percentage change on the individual tasks that showed significant treatment effects. There was a trend for greater improvement in the treatment group on the MFFT total correct on first attempt,  $F(1, 13) = 3.98, p = .07$ , but this failed to reach statistical signifi-

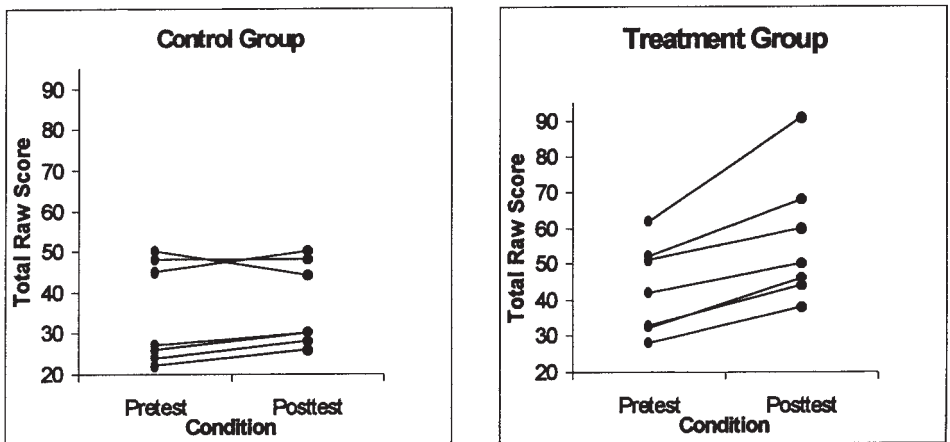


FIGURE 1 Individual scores for both the control and treatment groups on the Underlining Boxes Test for pre- and posttreatment.

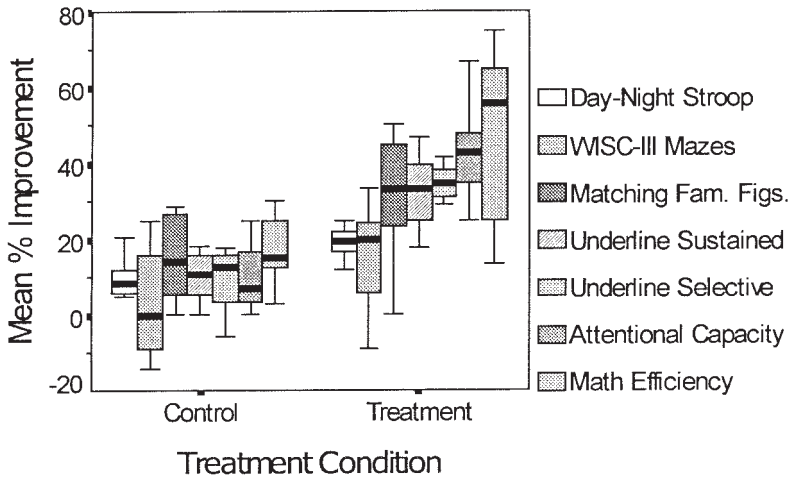


FIGURE 2 Box plots display, for both the control and treatment groups, the mean percentage improvement on the individual tasks for which treatment had an effect. Percentage improvement was calculated as  $\frac{\text{Post} - \text{Pre}}{\text{Pre}} \times 100$ .

cance. Interestingly, both groups showed an improvement in performance on this task, with the control group improving on average by 1.0 items,  $t(6) = -3.24, p = .018$ , and the treatment group by 2.4 items,  $t(6) = -3.97, p = .007$ . The MFFT latency showed no treatment effect. On the Day-Night Stroop Test, the treatment group made significantly more improvement than the control group,  $F(1, 13) = 12.57, p = .005$ . Again, both groups showed significant improvements, with the control group decreasing speed of response on average by 2.86 sec,  $t(6) = 2.46, p = .049$ , and the treatment group on average by 5.00 sec,  $t(6) = 8.10, p = .000$ .

Significant treatment effects were also seen on a measure of academic efficiency. On the Math Worksheets, there was a significant treatment effect,  $F(1, 13) = 47.93, p = .015$ . Once again, both groups demonstrated significant improvements in their performance, with the control group improving on average by 2.71 problems,  $t(6) = -7.55, p = .000$ , and the treated group by 6.86 problems,  $t(6) = -5.14, p = .002$ .

On tasks that did not show a treatment effect, a paired samples  $t$ -test procedure was utilized to determine if there were any nonspecific effects of being in an intervention study. Both groups did show significant improvements on the WISC-III Coding and Digit Span subtests. Average improvement on the Coding subtest was 5.0 points (raw score),  $t(13) = -2.85, p = .014$ , and 2.0 points (raw score) on the Digit Span subtest,  $t(13) = -5.75, p = .000$ . On the CCPT, there were no significant improvements in either the control or treatment groups on either total correct hits or commissions. A lack of any effect on this task was most likely due to the fact that both groups performed at ceiling, with the majority of the participants hitting

all targets and only rarely making any commission errors. Likewise, no effect was seen on the average latency on the MFFT. As anticipated, there were no changes pre- and posttreatment on the VOT for either group.

It is important to note that sample sizes for this study were small and that a large number of statistical tests were performed. Accordingly, some significant results may have capitalized on chance, and the overall probability of a Type I error likely exceeded 5% for the experiment. Setting the acceptable alpha too low, however, would reduce the power of being able to detect a group difference on tasks for which performance was anticipated to improve and increase the probability of a Type II error. We report exact  $p$  values for all analyses for which  $p$  was less than .05, and we caution the reader to interpret the results conservatively.

To summarize the psychometric pre- and posttest results, both groups improved significantly on a number of measures, supporting the impact of some degree of practice effect on these tasks, the impact of nonspecific training on video game activities, or both, as well as that due to specific attention training. However, the treatment group demonstrated significantly larger gains than the control group on the Mazes subtest of the WISC-III, the ACT, sections of the Underlining Test requiring sustained and selective attention, and the Day-Night Stroop, as well as on a measure of academic efficiency (Math Worksheets). There was a marginally significant effect of treatment on the MFFT total correct on first trial score. In contrast, there were no specific treatment effects on Coding, Digit Span, the CCPT, or the VOT.

Interestingly, there were no significant nonspecific or treatment effects seen on any of the scales of the ADDES. Scores on the inattention and impulsivity scales were combined, as some behaviors that were hypothesized to be impacted by the training were on both of these scales (e.g., failing to follow directions, needing oral questions and directions repeated, not remaining on task, and beginning assignments before receiving instructions). Parents of participants in both groups reported somewhat lower levels of combined inattention-impulsivity and hyperactivity following study participation, but none of these differences reached significance. In contrast, teachers reported some improvements in inattention and impulsivity for the treatment group,  $F(1, 111) = 4.25, p = .066$  (marginally significant), but no improvement for the control group. Teachers reported no differences in hyperactivity for either group.

## DISCUSSION

Overall, these results suggest that a direct treatment approach such as that utilized in the *Pay Attention!* materials can be effective for improving performance on several psychometric measures of sustained, selective, and higher levels of attention. In addition, changes were not noted on a measure of visual-spatial ability that we predicted would not be affected by a change in attentive abilities. Improvements were also noted in the treatment group on a measure of academic efficiency and in a



trend toward a significant improvement in teachers' ratings of inattentive-impulsive behaviors in the classroom. The findings lend support to the notion that systematic practice on attention demanding tasks can result in improved attentional performance.

Overall, the most improvement was noted on tasks of selective attention such as the ACT, the Day-Night Stroop, and the Underlining Test. Based on the Sohlberg and Mateer (1989a) model of attention, it was anticipated that significant gains would be seen on measures of simple sustained attention. Ceiling effects on the CCPT measure, however, may have limited the sensitivity of this task. Improvements in performance on the Underlining Test and the academic efficiency measures do support the notion that children made gains in their ability to sustain attention. Although this model of attention does provide a useful way of conceptualizing tasks and implementing treatment hierarchies, there are currently no real measurement tools developed from this model, and current tasks make demands on multiple aspects of attention.

As with other treatment-oriented investigations, the cause of these changes is not definite. One possibility is that the observed improvements reflected an improvement in underlying attentional capacity. Such changes have been hypothesized in other studies based on treatment-related electrophysiological changes. Alternatively, positive changes may be based on the learning of a strategy for regulating attention and arousal. This would be consistent with the work of Reid and Borkowski (1987) with impulsive children, suggesting that attention could be brought under some degree of voluntary control by self-instructional procedures.

A major goal of this study was to evaluate a set of attention training materials that had been designed specifically for children. All children appeared to enjoy the materials and readily engaged in the tasks. The linguistic and problem-solving demands of the tasks appeared to be appropriate for children in this age range. An important principle of attention training is to ensure that the basic linguistic and problem-solving demands of the task are well within the child's capability and that it is the attention demands of the tasks that are manipulated. Children had no difficulty understanding task demands, and some children even suggested new or more difficult tasks from the materials. As reported in adult samples, auditory tasks were typically more demanding than visual materials, perhaps due to their more fleeting temporal nature.

Although treatment effects were apparent across multiple measures, there were a number of significant improvements for both groups that were not related specifically to the treatment. It is interesting to speculate on the causes of these changes. Some of the changes were likely due to either practice or familiarity effects on the tasks themselves, increases in the children's abilities with increasing age and education, or both. Given that this study did not have a control group in which no intervention at all was provided, it is impossible to tell how much of the change noted was due to these factors versus how much may have been secondary to the effect of the control intervention. The control condition, although not providing any specific direct

intervention for attention ability, did provide a biweekly encounter with a therapist in which the children anticipated that they were working on improving their ability to pay attention. Additionally, there have been studies that have documented improvements in attention and concentration and motor speed secondary to use of non-specific computer programs (Larose, Gagnon, Ferland, & Pepin, 1989; see also Malec, Jones, Rao, & Stubbs, 1984). It is likely that some combination of these factors has resulted in the improvement seen in the control group.

Although the results of this intervention appear positive, this study has several limitations, including pre- and posttesting conducted by the researcher who provided the intervention, limited measures of generalizability, and the lack of a longer term follow-up. The fact that children in the study improved on psychometric measures of attention (which were different from the training materials) and on an academic task suggests that the gains seen on treatment materials generalized to other tasks. In addition, the reported trend for more attentive and less impulsive behavior in the treated group noted by the teachers also suggests some generalization of treatment gains. As teachers were blind to the status of treatment versus control for the children, this finding cannot be explained as a halo effect. Without any long-term follow-up study, however, it is not possible to determine if these gains are only time limited or whether they represent an enduring change in underlying ability. A longer term investigation is warranted to more adequately address this question and to provide a replication for these findings.

Also interesting to note is that some of the children in both groups were taking medication for ADHD throughout the study and assessments. Given the small sample size in this study, it was not possible to determine if medication status interacted with treatment status. The fact that improvement was seen in the treated group over and above the control group, despite the same proportion of both groups being medicated, lends support to the notion that medication does not preclude this type of intervention. It is anticipated that this type of treatment would be best delivered not in isolation of other treatment approaches but in concert with other interventions. Indeed, combined approaches are typically most beneficial in a number of disorders, and many researchers support a combined approach for children with ADHD (Barkley, 1997a; Everett, Thomas, Cote, Levesque, & Michaud, 1991; Whalen, Henker, & Hinshaw, 1985). Further investigation of medication status in combination with this type of intervention is also recommended. In addition to the positive cognitive aspects of this direct intervention approach, it is likely that children experience a gain in self-esteem and sense of control as they improve on treatment tasks. These types of gains, although not assessed directly through psychometric measurement of cognitive abilities, are likely to be beneficial in a number of domains and also warrant further investigation.

In conclusion, the results of this study provide additional support for the notion that direct intervention for attention is associated with gains in a number of attention tasks for children with ADHD. Although this approach has been used primar-

ily in individuals with acquired brain injury, this and other published data suggest that it may have utility for developmental deficits as well. Further research in this area is warranted with specific emphasis on examining generalizability of gains, long-term effects, and impact of medication status.

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## APPENDIX

### Pay Attention Tasks

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#### Sustained Attention Tasks

##### Visual sustained attention: I. Tasks

###### Card sorts into stacks

By single feature such as card color, hair color, hat or no hat, sex, age group, and so on.

By multiple features such as specific hair color, glasses, and so on.

###### House search

Find single items such as red things, flowers, things on wall, things on floor, and so on.

Find two items such as red things and things on walls, and so on.

##### Visual sustained attention: II. Examiner paced tasks

###### Card sorts

Participant has a response button and identifies when the target conditions have been met by the card the examiner places in front of them (e.g., people with brown hair and glasses, blonde followed by a brunette).

##### Auditory sustained attention: Tape Set I

Participants listen for targets and push a response button when they hear them. There are eight tapes, presented at both a slow and fast pace; tasks start simple and get more difficult (e.g., listen for the word *red*, *dog*, *red* or *yellow*, *B* words, things found in the sky, letters ascending, numbers descending, and so on).

#### Selective attention tasks

##### Visual selective attention: Visual distractors

Distracting visual overlays are placed over the house stimuli; searches are conducted as in the visual sustained attention tasks.

Visual tasks are completed as before, but now distracting noises (e.g., children playing on a playground) are played on tape while participants complete tasks.

(continued)

APPENDIX (Continued)

Auditory selective attention

Tapes are played as for auditory sustained attention, but there are distracting auditory stimuli in the background.

Tapes increase in complexity as before; distracting auditory stimuli include the sound of a heartbeat, a baby crying, someone telling a story, and children playing.

Alternating attention tasks

Visual alternating attention: House search

The participants have two objects for which they are searching in the house; they start searching for one object, using one specific pen color to mark it; when the examiner says switch, they must change pens and then begin looking for the second object that they were told to find (e.g., green things and things on walls).

Visual alternating attention: Cards

Sorting into two stacks by identifying features which examiner switches (e.g., glasses to hats).

Auditory alternating attention

Listening for two target words, first word first; then examiner says "Switch" and participant listens for the new word; examiner may switch several times; targets include dog and cow, for example.

Divided attention tasks

Visual divided attention: Card sort

Participant sorts cards into stacks depending on some target criteria, but has an additional rule, so that cards that meet an additional criteria are not only sorted into the correct pile but placed face down (e.g., sort by family, boys face down).

Auditory-visual divided attention: Card sort or house and tapes

Participants have two tasks which they do simultaneously. For example, they may be sorting cards into stacks using some criteria and also listening to a tape for a target word, for which they must quickly hit the response button. For example, they may cross out red things in the houses while listening for words that begin with *B*.

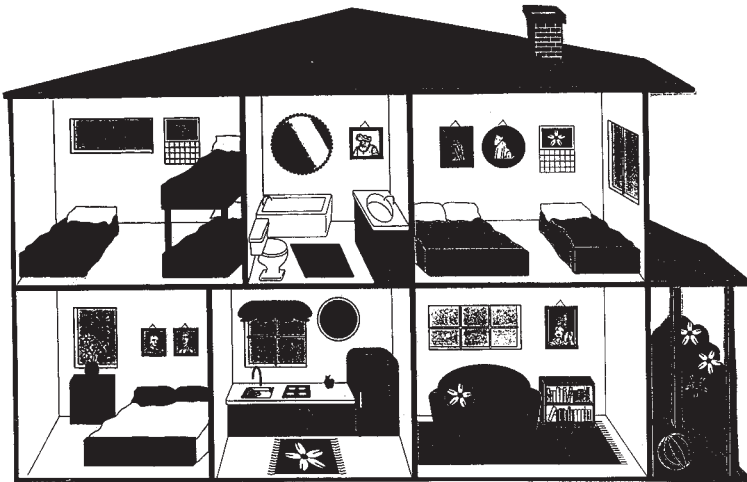


FIGURE A1 Example of a house for one of the families in *Pay Attention!*



FIGURE A2 Example of family member character cards. The background color of a card is the same color as the last name of the family to which that the pictured character belongs (e.g., all members of the Green family are pictured on green cards).



Review

# The cognitive neuroscience of sustained attention: where top-down meets bottom-up

Martin Sarter\*, Ben Givens, John P. Bruno

*Department of Psychology, The Ohio State University, 27 Townshend Hall, Columbus, OH 43210, USA*

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## Abstract

The psychological construct ‘sustained attention’ describes a fundamental component of attention characterized by the subject’s readiness to detect rarely and unpredictably occurring signals over prolonged periods of time. Human imaging studies have demonstrated that activation of frontal and parietal cortical areas, mostly in the right hemisphere, are associated with sustained attention performance. Animal neuroscientific research has focused on cortical afferent systems, particularly on the cholinergic inputs originating in the basal forebrain, as crucial components of the neuronal network mediating sustained attentional performance. Sustained attention performance-associated activation of the basal forebrain corticopetal cholinergic system is conceptualized as a component of the ‘top-down’ processes initiated by activation of the ‘anterior attention system’ and designed to mediate knowledge-driven detection and selection of target stimuli. Activated cortical cholinergic inputs facilitate these processes, particularly under taxing attentional conditions, by enhancing cortical sensory and sensory-associational information processing, including the filtering of noise and distractors. Collectively, the findings from human and animal studies provide the basis for a relatively precise description of the neuronal circuits mediating sustained attention, and the dissociation between these circuits and those mediating the ‘arousal’ components of attention. © 2001 Elsevier Science B.V. All rights reserved.

*Theme:* Neural basis of behavior

*Topic:* Cognition

*Keywords:* Attention; Cortex; Acetylcholine; Basal forebrain

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\*Corresponding author. Tel.: +1-614-2921-751; fax: +1-614-6884-733.

*E-mail address:* sarter.2@osu.edu (M. Sarter).

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## 1. Introduction

Beginning with Mackworth’s experiments in the 1950s, the assessment of sustained attention (or vigilance) performance typically has utilized situations in which an observer is required to keep watch for inconspicuous signals over prolonged periods of time. The state of readiness to respond to rarely and unpredictably occurring signals is characterized by an overall ability to detect signals (termed ‘vigilance level’) and, importantly, a decrement in performance over time (termed ‘vigilance decrement’). The psychological construct of ‘vigilance’, or ‘sustained attention’, has been greatly advanced in recent decades, allowing the development and validation of diverse tasks for the test of sustained attention in humans and animals and thereby fostering research on the neuronal circuits mediating sustained attention performance in humans and laboratory animals.

Sustained attention represents a basic attentional function that determines the efficacy of the ‘higher’ aspects of attention (selective attention, divided attention) and of cognitive capacity in general. Although impairments in the ability to detect and select relevant stimuli or associations are intuitively understood to impact modern living skills (e.g., driving a car), cognitive abilities (e.g., acquiring novel operating contingencies of teller machines, or detecting social cues important to communicate effectively), and possibly even consciousness [74], psychological research on sustained attention has largely focused on parametric, construct-specific issues and only rarely addressed the essential significance of sustained attention for higher cognitive functions like learning and memory [17]. In fact, the evidence in support of the fundamental importance of sustained attention for general cognitive abilities has largely been derived from studies in neuropsychiatric populations (see below). Thus, determining the brain networks mediating sustained attention not only represents a crucial step toward understanding the neuronal mechanisms underlying this critical cognitive function, but also toward the development of cognitive neuroscience-inspired theories of neuropsychiatric disorders characterized by impairments in fundamental attentional functions (see below).

Cognitive neuroscience research has consistently documented activation in right hemispheric prefrontal and parietal regions during sustained attention performance.

The recent overview by Cabeza and Nyberg [8] illustrates the sobering degree to which such imaging data remain isolated if they are not embedded in a theory describing the neuronal mediation of the cognitive performance of interest. As we have argued earlier [85], the development of such a theory requires converging evidence from studies manipulating the cognitive function of interest (i.e., sustained attention) and measuring brain correlates (typically human imaging studies) with results from experiments on the consequences of manipulations in the integrity, excitability, or integrative capacity of defined neuronal circuits on the cognitive function of interest (typically animal behavioral–neuroscientific studies). Such converging evidence ensures that research aimed at explaining complex high-level cognitive functions by successively lower neural levels of description benefits from neuroscientific research approaches, and that efforts to determine low-level neuronal mechanisms of cognitive functions benefit from cognitive construct-driven research in humans [25,63,76]. Furthermore, it is crucial that evidence in support of neuronal circuits acting top-down to modulate attentional information processing (e.g., Ref. [75]) will be integrated with evidence on the role of ascending cortical input systems to arrive at a comprehensive theory of sustained (or any other form of) attention. In other words, the title phrase ‘where-top down meets bottom-up’ reflects two interrelated issues, that is (1) the convergence of information generated by cognitive-neuroscience research in humans and by the more fundamental neurosciences that is required to attribute sustained attention to defined neuronal circuits [85], and (2) the convergence of the functions mediated via top-down cognitive processes and bottom-up sensory input processing that is crucial for sustained attentional performance. These convergences are the focus of this review, indicating that the different levels of analysis employed by cognitive neuroscience research on sustained attention have sufficiently developed, albeit largely separately, to permit now an integration of evidence and therefore the development of a theory about the neuronal mediation of sustained attention.

### 1.1. Top-down versus bottom-up

The terms ‘top-down’ and ‘bottom-up’ processes, and the special focus of this review, require further clarification. ‘Top-down’ or ‘bottom-up’ regulation of attentional

processes represent conceptual principles rather than referring to anatomical systems, such as ascending and descending projections. ‘Top-down’ processes describe knowledge-driven mechanisms designed to enhance the neuronal processing of relevant sensory input, to facilitate the discrimination between signal and ‘noise’ or distractors, and to bias the subject toward particular locations in which signals may appear [41]. For example, in sustained attention performance, the subject knows where to expect what type or modality of signal, how to respond in accordance with previously acquired response rules, and so forth. Furthermore, the subject develops expectations concerning the probability for signals and strategies for reporting signals versus false alarms (see below). All these variables influence performance, based on mechanisms that range from changes in sensory signal processing to the enhanced filtering of distractors and the modification of decisional criteria.

Such a ‘top-down’ biasing of attentional performance contrasts with ‘bottom-up’ perspectives that describe attentional functions as driven mainly by the characteristics of the target stimulus and its sensory context [97]. ‘Bottom-up’ perspectives attempt to explain a subject’s ability to detect targets and target-triggered attentional processing largely by the sensory salience of the targets, and their ability to trigger attentional processing by recruiting ‘higher’ cortical areas in a bottom-up manner (e.g., from the processing of a visual target in the primary visual cortex to temporal regions for object identification and to parietal regions for location). Importantly, ‘top-down’ and ‘bottom-up’ processes represent overlapping organizational principles rather than dichotomous constructs, and in most situations, top-down and bottom-up processes interact to optimize attentional performance [22].

Activation of top-down processes are traditionally considered a component of the frontal cortical mediation of executive functions. Such processes were previously conceptualized in the context of attention by Posner and Petersen’s [75] anterior and posterior attention systems that function to detect targets and bias the subjects’ orientation to target sources, respectively. Data from human imaging and primate single unit recording studies have substantiated the notion of top-down processes by demonstrating sequential activation of frontal-parietal-sensory regions, including decreases in activity in task-irrelevant sensory regions, and the modulation of neuronal activity in sensory and sensory-associational areas reflecting the top-down functions described above [19,39,41,93]. This review focuses on the functions of the basal forebrain cholinergic projections to the cortex as a major component of the activation of top-down processes in the mediation of sustained attention. To avoid confusion, it should be reiterated that therefore, the *anatomically ascending* basal forebrain system is proposed to contribute to the *functionally top-down* processes in sustained attention.

As will be discussed below, the activation of cortical

cholinergic inputs as a major component of the top-down processes in sustained attention performance acts to bias the processing of sensory inputs at all levels of cortical sensory information processing, thereby facilitating and maintaining sustained attention performance. Fig. 1 captures this hypothesis by illustrating the anterior attention system and its top-down regulation of posterior and sensory cortical information processing ([75]; see also legend for Fig. 1). The basal forebrain cholinergic corticopetal projection system is conceptualized as a major and necessary component of these top-down processes. In sustained attention, this projection system is activated, via direct connections from the prefrontal cortex to the basal forebrain. Increased activity in cortical cholinergic inputs, that terminate in all cortical regions and layers, facilitate all aspects of the top-down regulation of sustained attention performance, ranging from the enhanced sensory processing of targets to the filtering of distractors and the optimization of decisional strategies. Evidence in support of this hypothesis will be discussed in detail, following a description of the construct ‘sustained attention’.

## 2. Sustained attention: components of a construct

### 2.1. ‘Sustained attention’ and ‘arousal’: conceptual overlaps and differences

As the terms ‘vigilance/sustained attention’ and ‘arousal’ have been used interchangeably, particularly in clinical contexts and in interpreting electroencephalographic (EEG) data, the specific meaning of vigilance/sustained attention needs to be defined and dissociated from the more global classification of brain states that include ‘arousal’. Obviously, the ability to perform monitoring tasks requires an activated forebrain and thus depends on ‘arousal’. Likewise, the ‘arousing’ consequences of novel, emotional, or stressful stimuli initiate and interact with attentional performance. However, the operational definition of sustained attention, and the measures generated to assess sustained attentional performance, are specific and dissociable from the concept of ‘arousal’. While changes in ‘arousal’ typically are deduced from brain activity data (such as EEG data), an interpretation of data in terms of ‘sustained attention’ is necessarily based on behavioral performance data (e.g., detection rates, false alarm rates, etc.). As will be discussed further below, such a conceptual dissociation between arousal and sustained attention performance as well as the interactions between both constructs are supported by the organization of the neuronal circuits mediating these functions.

### 2.2. Sustained attention: variables and measures

#### 2.2.1. Variables taxing sustained attention performance

Similar to other attentional capacities, the capacity to

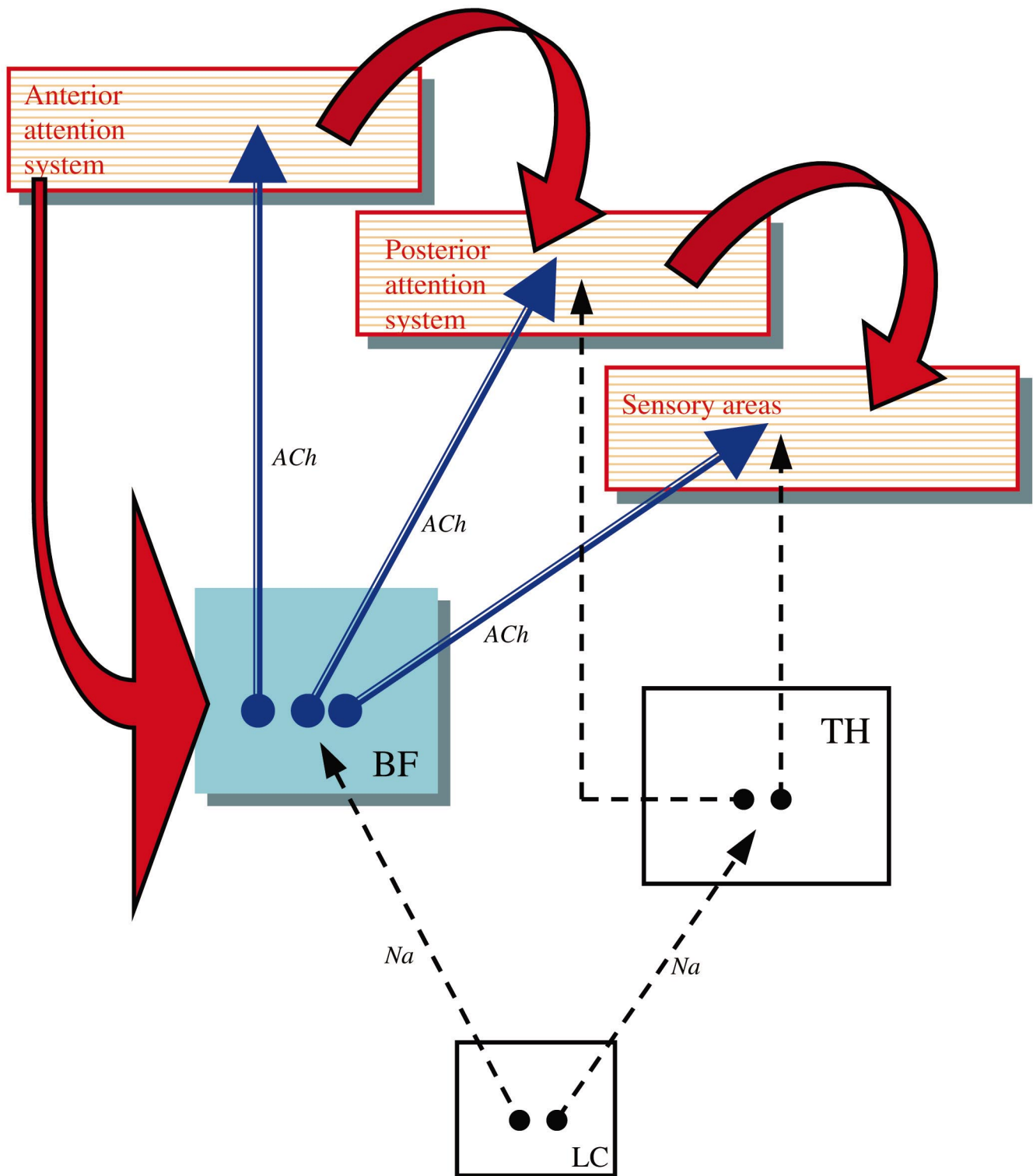


Fig. 1. Schematic illustration of the major components of a neuronal network mediating sustained attention performance. The figure combines anatomical and functional relationships and represents a conceptual summary of the evidence from human neuropsychological and imaging studies and animal experimental approaches. Neuroimaging studies demonstrated consistent activation of right medial frontal and dorsolateral prefrontal cortical regions, as well as parietal cortical regions in subjects performing in sustained attention tasks. Activation of the 'anterior attention system' [75] has been suggested to modulate top-down the functions of posterior cortical areas, thereby enhancing and biasing sensory input processing in primary sensory through sensory-associational regions (curved arrows). Animal experiments determined the crucial role of cortical cholinergic inputs in sustained attention (ACh, acetylcholine). Activation of basal forebrain (BF) corticopetal cholinergic projections is necessary for sustained attention performance, and cortical cholinergic inputs may mediate, or at least critically contribute to, the activation of fronto-parietal regions. Furthermore, cholinergic inputs to the cortex mediate the facilitation of bottom-up sensory information processing. Activation of the cholinergic corticopetal projections represents a component of the top-down regulation associated with the recruitment of the anterior attention system (left arrow). The ability of 'arousal'-inducing stimuli to trigger attentional processing is mediated bottom-up largely via noradrenergic (Na) projections originating in the locus coeruleus (LC) and terminating in the thalamus (TH) and the basal forebrain.

sustain attention has been considered to represent a limited resource. Several variables have been demonstrated and conceptualized as taxing sustained attention performance [65,67]. (1) The successive (as opposed to the simultaneous) presentation of signal and non-signal features taxes sustained attention performance. (2) High event rate, that is the frequency of signal events, combined with unpredictability of the time of the presentation of the event (termed event asynchrony) and of the event type (e.g., signal vs. non-signal), enhances the demands on sustained attention performance. High event rates also represent a critical variable in the manifestation of a vigilance decrement. (3) Spatial uncertainty about the locus of event presentation also promotes the manifestation of vigilance decrements. (4) The use of dynamic (as opposed to static) stimuli, such as signals with variable luminance or duration also fosters the manifestation of a vigilance decrement, partly because the presentation of dynamic stimuli is associated with decreased discriminability. (5) Demands on working memory (as, for example, occurring in tasks with successive event presentation) tax sustained attention performance. (6) Using signals with conditioned or symbolic significance, thus requiring additional processing to report detection (as opposed to the pure detection of signals) is thought to foster the exhaustion of the sustained attention capacity. Such signals are considered to increase the demands for the ‘controlled processing’ of signals and thus to increase the allocation of resources consumed by the attentional task.

### 2.2.2. Practice

In experiments with human subjects, practice of sustained attention tasks typically is kept at a minimum in order to limit the degree to which task performance is mediated by highly automated attentional processing and to prevent the disappearance of the vigilance decrement [27]. Different levels of practice may account for a substantial proportion of conflicting data in the literature, and although the issue is widely recognized, the effects of practice on vigilance performance remain insufficiently investigated. Furthermore, extensive practice and the resulting high level of automatism may not necessarily decrease the demands on processing resources to the extent assumed in earlier theories. Conceptualizations of sustained attention as a process in which an ‘attentional supervisory system’ maintains target schemata that correspond with the actual detection requirements predict that the functions of this system consume processing resources even in well-practiced tasks, therefore producing performance decrements over time-on-task [95].

### 2.2.3. Reaction time versus number of detected signals and false alarms

In highly practiced vigilance tasks in which subjects exhibit high levels of detections of signals and low levels of false alarms, reaction time may become the critical

measure of performance. Increased reaction times usually correlate with decreased detection rates, supporting the hypothesis that the former measure also indicates vigilance decrements. In humans, reaction times may increase several hundred milliseconds during monitoring tasks that last over an hour. In animals, reaction times have been analyzed and interpreted with great caution, specifically following manipulation of neuronal functions, as they are potentially confounded by a multitude of sensory and motor variables and competing behavioral activities.

### 2.2.4. Changes in sensitivity versus shift in criterion

Data generated by traditional vigilance tasks have been routinely analyzed using signal detection theory, to the extent that vigilance and signal detection theory have been considered interchangeable terms, and ignoring the fact that the latter in essence represents a statistical method. However, an analysis of sustained attention performance data using signal detection theory may provide the quantitative basis for interpreting changes in vigilance performance. Specifically, the number of signals detected is a combined result of signal detectability (or sensitivity) and the subject’s criterion or ‘willingness’ to report detection of a signal. The former depends largely on the psychophysical characteristics of the signals relative to non-signals, while the latter is a more complex function of the subjects’ general strategy, task instructions (e.g., performing in accordance with a conservative versus a risky criterion), and of task parameters such as cost/benefit considerations for reporting signals and false alarms. For example, a decline in the number of hits, that is the correct detection of signals, over a prolonged period of time may be due to an increasingly conservative criterion. Experimentally-induced increases in the probability for a signal typically result in a loosening of the criterion that is reflected by increases in hits and false alarms. Conversely, changes in performance in high event-rate, successive discrimination paradigms may be due rather to a decline in sensitivity. Signal detection theory-derived analyses potentially assist in dissociating the contribution of shifts in sensitivity and criterion to changes in vigilance performance [96].

## 3. Macroanatomical correlates

### 3.1. General interpretational issues

Macroanatomical correlates of sustained attention performance have been determined mainly by two lines of research. First, findings from neuropsychological studies have identified areas of brain damage or degeneration which are correlated with impairments in sustained attention performance. Second, and more recently, functional imaging studies have located areas in the intact brain in

which changes in metabolic activity correlate with sustained attention performance.

Complexities in the interpretation of brain damage in terms of determining the normal functions of the brain region of interest, although remaining a persistent topic in the literature, deserve continued and careful scrutiny. First, the functional consequences of the absence of a brain region routinely have been interpreted as indicating this area's functions in the intact brain, ignoring the more appropriate view that residual performance reflects the processing maintained by the residual brain. This interpretational concern arises in part from, and is further convoluted by, the often implicit conception of a particular brain region as a functionally distinct unit rather than representing a functionally critical node or intersection of multiple neuronal networks [25]. For example, the prominent (and seemingly compulsory) involvement of prefrontal cortical areas in diverse cognitive functions [8,21,92] may be associated with its central position within cortical associational, limbic and paralimbic neuronal networks rather than, or at least in addition to, the specific cognitive operations mediated via intra-prefrontal neuronal circuits [56].

The second interpretational issue concerns implicit assumptions underlying attempts to map complex cognitive functions onto brain structures. The prime issue concerns the assumption that the cognitive function of interest (e.g., sustained attention) represents a relevant functional unit that maps on, or is isomorphic with, a traditionally defined neuroanatomical region or neuronal system. Below, the converging evidence from neuropsychological and functional imaging studies, indicating that sustained attention maps onto macroanatomical structures such as the prefrontal cortex, with evidence from studies in animals, showing that neuronal manipulations of the activity of cholinergic inputs modulate sustained attention performance, is suggested to provide the basis for a description of the neuronal circuits mediating sustained attentional abilities.

### *3.2. Sustained attention following brain damage and neuronal degeneration*

Damage to the frontal cortex as well as lesions in the (inferior) parietal lobe, result in decreases in the number of hits, increases in reaction time, and in the manifestation or augmentation of a decrement in sustained attention performance over time-on-task (e.g., Refs. [83,84]). The detrimental effects of distractors on sustained attention performance appear to be particularly prominent in patients with right frontal lobe damage, while the performance of patients with parietal lesions generally is more sensitive to the effects of high event rates (but see Ref. [3]). The specificity of interpretations of the effects of right fronto-parietal damage in terms of impairments in sustained attention [81] has been supported by studies which excluded the possibility that increased fatigue, differential

effects of practice, or differences in motivational processes significantly confound impairments in vigilance performance in these patients [29].

Aged humans and, more dramatically, patients with age-related dementias exhibit lower detection rates in continuous performance tasks and other standard neuropsychological tests that assess an insufficiently defined blend of arousal and vigilance functions. As the majority of the available studies conducted in patients with Alzheimer's disease did not selectively assess sustained attention [66], the reliability of demonstrating a vigilance decrement in these patients has remained unsettled. Most likely, the demonstration of such effects depends on the degree to which tasks demand the sustained and effortful monitoring and processing of stimuli, thereby presumably taxing fronto-parietal functions. Likewise, the extent to which impairments in sustained attention can be demonstrated, similar to impairments in selective and divided attention, in early stages in Alzheimer's disease, is unclear [71]. In general, however, the assumptions about the neurobiological bases for the attentional impairments in Alzheimer's disease, including the decline in sustained attention, have generally followed the fronto-parietal conceptualizations of attentional functions and thus attributed impairments to prefrontal dysfunction [66], despite these patients having more widespread damage that includes parietal cortical and subcortical, specifically basal forebrain, regions.

### *3.3. Evidence from functional neuroimaging studies*

The extent to which evidence from lesion studies and functional imaging studies agree is remarkable. Anterior cingulate and dorsolateral prefrontal as well as parietal cortical regions, located primarily but not exclusively in the right hemisphere, have been consistently found to be activated in subjects performing sustained attention tasks, irrespective of the modality of stimuli used in these tasks [11,13,26,68]. Furthermore, a decline in activity in fronto-parietal-temporal regions over the course of task performance has been suggested to mediate vigilance decrements [16,69].

In addition to the modality-independent activation of right fronto-parietal regions during sustained attention, demands on monitoring and discriminating stimuli of a particular modality necessarily activate sensory cortical regions as well as sensory associational areas [12,26]. Collectively, the findings from functional imaging studies have supported a general model that describes sustained attention as a 'top-down' process that begins with the subject's general readiness to detect and discriminate information, mediated largely via right fronto-parietal regions, and which enhances the perceptual and spatial processes that contribute to sustained attention performance via activation of posterior parietal areas and facilitation of the processing of sensory inputs in primary and

secondary sensory and sensory-associational regions ([39,46]; see also the discussion in Refs. [13,75]). This concept of a top-down facilitation of perceptual components of attentional processes corresponds with the increases in responsiveness and selectivity of single cell firing activity observed in sensory associational areas under conditions of increased demands on attention [18].

#### 4. Neuronal circuits mediating sustained attention performance

Evidence from studies designed to manipulate the functioning of defined neuronal circuits and assess the consequences for attentional performance, or to record from neurons constituting such circuits in animals performing in attentional tasks, is expected to explain the prominent role attributed to frontal cortical and parietal regions in human neuropsychological and functional imaging studies. Such reductionist explanations are also expected to specify the nature of the processing mediated via frontoparietal cortical areas in sustained attention, and to determine the specific neuronal circuits responsible for the activation of these areas observed in imaging studies or for the impairments in sustained attention resulting from damage or degenerative processes in these areas. Although the focus of the present discussion is on the neuronal mechanisms mediating sustained attention in the human brain, evidence from animal experimental approaches therefore represents a necessary component of such an analysis.

##### 4.1. Animal behavioral tests of sustained attention

Animal experimental approaches to the study of the neuronal mechanisms of attention only recently have become viable as tasks for the measurement of different aspects of attention became available. These tasks were designed and demonstrated to be valid in accordance with the criteria constituting the psychological construct (above). Two tasks for use in rats have been extensively used for the study of sustained attention. First, Robbins, Everitt, and co-workers (e.g., Ref. [78]) employed the ‘5-choice serial reaction time task’ that requires animals to monitor the location of a briefly presented light in one out of five spatially arranged target areas. This task combines aspects of the continuous performance tasks used in human studies and primarily tests sustained spatial attention. Second, an operant task requiring rats to detect signals and to discriminate between signals and non-signals was designed to generate a complete set of response categories (hits, misses, false alarms, correct rejections). Importantly, a false alarm in this task represents a discrete ‘claim’ for a signal in a non-signal trial, therefore overcoming the limitations of the response rate-confounded calculation of false alarm rates in more traditional signal detection tasks

used in animal research. The impact of parametric manipulations of task variables, distractors, event rate, or the probability for signals supports the validity of the measures of performance generated by this task in terms of indicating sustained attention ([52]; for a version of this task used in humans see Ref. [48]). Similar to tasks used in human research, significant vigilance decrements in intact animals were not always reliably observed, but usually emerged in interaction with detrimental neuronal manipulations (see below).

##### 4.2. Basal forebrain corticopetal cholinergic projections: a necessary component of the neuronal circuits mediating sustained attention

The basal forebrain corticopetal cholinergic projections terminate in practically all areas and layers of the cortex (for review see Ref. [87]). For several decades, human and animal psychopharmacological experiments on the effects of nicotine and muscarinic receptor antagonists (such as scopolamine and atropine) have strongly implicated cholinergic systems in sustained attention. Beginning with the demonstration of the effects of excitotoxic lesions of the basal forebrain on rats’ performance in the five-choice reaction time and other tasks and on the performance of monkeys in a version of Posner’s overt orientation task (e.g., Refs. [7,59,79,102]), the crucial dependency of attentional abilities on the integrity of this system has been extensively explored. Collectively, the available evidence from studies on the effects of loss of cortical cholinergic inputs demonstrates the following: (1) selective lesions of the basal forebrain corticopetal cholinergic projections, produced by infusions of the cholinotoxin 192 IgG-saporin into the region of the nucleus basalis of Meynert and the substantia innominata in the basal forebrain, are sufficient to produce profound impairments in sustained attention [50]. (2) The lesion-induced impairment in performance is restricted to signal trials while correct rejections remain unaffected, reflecting the absence of the normally augmenting effects of cortical acetylcholine (ACh) on the processing of sensory inputs (e.g., Refs. [54,62,98,103]). Moreover, such lesions decrease the vigilance levels and augment the vigilance decrement [50]. (3) Loss of cortical cholinergic inputs alone, as opposed to loss of all basal forebrain cholinergic efferents, suffices to produce such impairments [53]. (4) The impairments in sustained attention observed following cortical cholinergic deafferentation are persistent and do not recover, even following extended periods of daily practice of performance [50]. (5) The extent of the impairments in sustained attention is tightly correlated with the degree of loss of cortical cholinergic inputs, particularly in fronto-dorsal cortical areas [50].

Evidence from studies designed to manipulate the excitability of basal forebrain corticopetal cholinergic projections confirmed the crucial role in cortical cholinergic

gic inputs in sustained attention performance. For example, infusions of positive or negative modulators of GABAergic (GABA;  $\gamma$ -aminobutyric acid) transmission into the basal forebrain, that augment or decrease, respectively, the ability of GABA to inhibit the excitability of corticopetal cholinergic projections [58,86], bidirectionally alter sustained attention performance. Specifically, augmentation of GABAergic inhibition in the basal forebrain of rats trained in a sustained attention task produced transient lesion-like effects characterized by a selective decrease in the animals' ability to detect visual signals. Conversely, infusions of a negative GABA-modulator into the basal forebrain increased the number of false alarms, that is the number of 'claims' for signals in non-signal trials [38]. The latter effect can be interpreted as reflecting an abnormal over-processing of the stimulus situation, mediated via disinhibition of cortical cholinergic inputs. Likewise, infusions of an antagonist for glutamatergic NMDA receptors (APV) into the basal forebrain produce effects on sustained attention performance that resemble those of cholinergic lesions or of positive GABA modulators. Conversely, infusions of NMDA, which augment cortical ACh release [24], resulted in an increase in false alarms similar to those produced by a negative GABA modulator [100]. These and other data have consistently supported the hypothesis that modulation of the activity of cortical cholinergic inputs mediate changes in performance in sustained attention [87].

The focus on cortical cholinergic inputs in the mediation of sustained attention is not based solely on the effects of lesions or of manipulation of the excitability of corticopetal projections. Recent studies demonstrated that ACh release in the cortex in animals performing a sustained attention task is correlated with demands on sustained attention [36]. While increased cortical ACh release was associated generally with attentional task performance, recovery of performance following the presentation of a visual distractor was distinctively associated with increases in ACh release. Furthermore, performance of simple operant procedures controlling for the effects of lever presses for food reward, movement in the operant chambers and the presentation of visual stimuli was not associated with increases in cortical ACh release [35].

The hypothesis that distractor-induced increases in the demands for sustained attention are mediated via cortical cholinergic inputs has also been supported by neurophysiological evidence. Single neuron recording studies in the medial prefrontal cortex (mPFC) revealed that mPFC neurons are engaged in multiple aspects of sustained attention performance, including response and reward rate [31]. Importantly, the baseline level of spontaneous activity in a defined population of mPFC neurons systematically increased when a visual distractor was present during attentional performance. In the current context, this distractor-induced increase in mPFC neural activity is hypothesized, in a top-down fashion, to enhance the processing of

sensory inputs in other more posterior cortical areas. Furthermore, glutamatergic projections from the prefrontal cortex to the basal forebrain [107] contribute to the activation of basal forebrain corticopetal projections [24]. Thus, this prefrontal–basal forebrain–cortex circuit represents a component of the PFC-controlled top-down effects, collectively functioning to bias the subject toward the specific attentional demands at hand (see below for further discussion). Critical support for the role of acetylcholine in this modulation of attention comes from the observation that the distractor-induced increases in mPFC unit firing were no longer observed following unilateral cholinergic deafferentation restricted to the recording area ([31]; Fig. 2).

The absence of distractor-induced increases in spontaneous activity of mPFC neurons following local cholinergic deafferentation of the recording area suggests that the cholinergic input to these neurons enhances their excitability. According to present hypotheses, when a visual distractor is introduced during task performance, the basal forebrain cholinergic system becomes activated in proportion to the level of attention required to maintain performance (see also Ref. [47]), which subsequently leads to increased unit firing in those neurons most tightly coupled to the cholinergic afferents, either directly or through local synaptic interactions. Alternatively, the increase in activity can be thought of not as being driven, but rather as 'monitoring' the level of basal forebrain activation. When the basal forebrain is activated, under conditions of high attentional demand, a subset of neurons in the mPFC detect this change and elevate their activity and subsequently project this enhanced activity to the posterior cortical regions to modulate the processing of signals.

The loss of distractor-induced increases in unit activity following cholinergic deafferentation of the recording area is not confounded by alterations in behavioral performance as evidenced by the fact that the restricted, unilateral deafferentation of mPFC cholinergic inputs had no effect on sustained attentional performance. In other words, the loss of distractor-induced increases in unit activity is solely attributed to the loss of cholinergic input to the region of the recorded neurons. The lack of attentional effects of the restricted cholinergic deafferentation should not be taken to indicate that this region of cortex is not critically dependent on cholinergic input for attentional performance. On the contrary, bilateral medial prefrontal cholinergic deafferentation, produced by bilateral infusions of 192 IgG-saporin into the mPFC, resulted in highly selective impairments in sustained attention, that is a loss of signal detection accuracy during the presence of a visual distractor, but not under standard attentional conditions [30].

The lack of effect of bilateral mPFC cholinergic deafferentation on performance under standard attentional conditions suggests that mPFC cholinergic inputs may have less of a role in enhancing signal detection and more of a role in filtering out the distractor. Thus, prefrontal



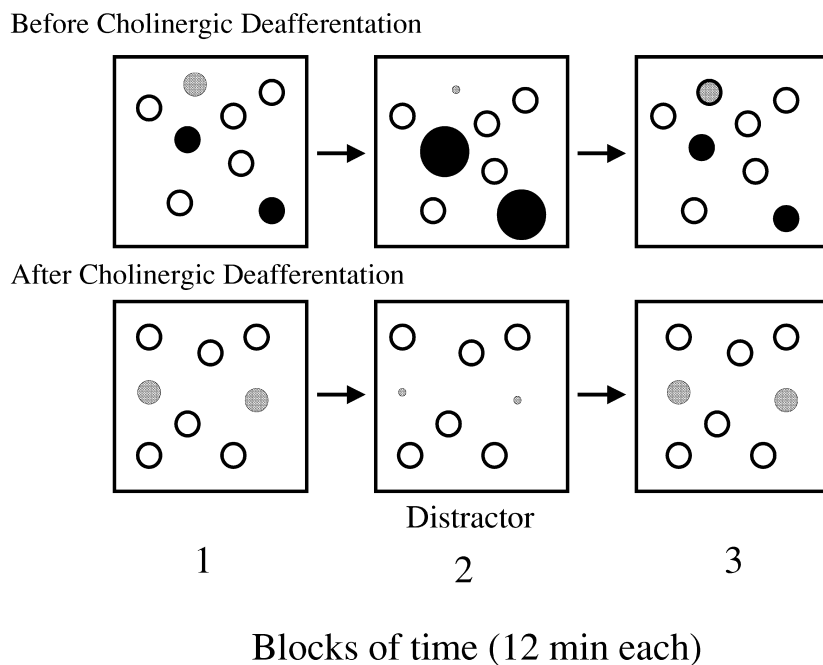


Fig. 2. Representation of attentional correlates of neural activity in the medial prefrontal cortex (mPFC) before and after local cholinergic deafferentation during the presence (block 2) or absence (blocks 1 and 3) of a visual distractor. Each circle represents a single pyramidal neuron with its size indicating its rate of activity. Three types of neurons, defined post-hoc, are shown: those that increase (black), decrease (gray) or do not change (white) activity in the presence of the distractor. Prior to the cholinergic lesion, a population of neurons (black circles) displays distractor-induced increases in activity and a smaller population show distractor-induced decreases (gray circles). After the cholinergic lesion, neurons with distractor-induced increases are no longer observed, and there is a doubling of the proportion of neurons with distractor-induced decreases. The loss of distractor-induced increases following deafferentation indicates the importance of basal forebrain cholinergic afferents in the attentional modulation of the mPFC.

circuits may contribute to signal processing by modulating the transfer of sensory information in posterior cortex and by suppressing distracting sensory information. Both the distractor-suppressing and signal-enhancing functions are supported by, and in fact depend on, proper cholinergic stimulation in all cortical areas mediating these functions, and such cholinergic stimulation is maintained in part by the direct feedback from the mPFC to the basal forebrain (see Fig. 1). Moreover, as increases in cortical ACh release are associated with standard task performance, and specifically with the increased attentional efforts supporting the recovery of performance following the presentation of a distractor [36], the available data collectively suggest that the integrity of mPFC cholinergic inputs is necessary for sustained attentional performance under the condition of distractor-induced increases in demands on attentional processing. In contrast, cholinergic inputs to specifically the mPFC are not necessary for standard sustained attention performance, but the integrity of cholinergic inputs to greater parts of the cortex is necessary for such performance [50]. This dissociation further supports the dual functions mediated via an activated basal forebrain corticopetal cholinergic projection system, that is contributing to the activation of the prefrontal cortex which is crucial for filtering distractors and recruiting top-down processes and, simultaneously, interacting with bottom-up processes

to gate and enhance the processing of sensory inputs at all levels of cortical input processing (Fig. 1).

Furthermore, the same mPFC neurons that are thought to modulate or bias signal processing in posterior cortical sites are simultaneously engaged in the reward and response aspects of task performance, and their response characteristics do not change as a function of attentional demand ([31]; see also Ref. [91]). Thus, the presence of the visual distractor, which resulted in more demanding attentional conditions and produced deficits in signal detection accuracy, did not alter the behavioral correlates of unit activity indicating that the mPFC is engaged in both cognitive and non-cognitive components of performance. This observation suggests that, in the mPFC, the function of cholinergic inputs to filter distractors and to mediate general operant performance may also be differentiated. Future studies need to be designed to distinguish further between, and to gauge the relative contributions of, these two components of the effects of activated cortical cholinergic inputs to the mPFC and the entire cortex.

#### 4.3. Afferent and efferent components of the corticopetal cholinergic system

The hypothesis that sustained attention performance is mediated by cholinergic inputs to widespread areas of the

cortex implies that cholinergic inputs are not ‘pre-wired’ for all possible stimuli, and that cortical ACh-mediated enhancement of the processing of sensory and associational information occurs in a rather cortex-wide fashion. Furthermore, cognitive/behavioral specificity of the effects of ACh is hypothesized to result from interactions with other, converging (e.g., thalamic and associational) inputs (for more discussion see Ref. [87]). For example, ACh-mediated increases in the responsivity of auditory cortical neurons to stimuli, the enhancement of the auditory response selectivity of these neurons and, generally, ACh-mediated facilitation of the detection and discrimination of auditory inputs, are due to interactions between activated cortical cholinergic and thalamic inputs converging in the auditory cortex [104]. In the visual cortex, evidence in support of a cholinergically-mediated enhancement of intralaminar transfer of information between cortical columns suggest that the effects of ACh in sensory areas go beyond facilitation of sensory inputs and include enhancement of higher perceptual processes [43,106]. Compared to the effects of ACh in sensory cortex, information about the effects of ACh on the firing properties of individual neurons in associational areas is scarce. Generally, ACh produces a complex combination of effects on the excitability of cortical interneurons and efferent projections which, collectively, acts to enhance the ability of cortical neurons to process subcortical or associational inputs [33], and thus the processing of conditioned or behaviorally significant stimuli. Thus, the distractor-associated, cholinergically-mediated changes in prefrontal neuronal activity (above) presumably reflect the interactions between increases in the activity of cholinergic inputs to these areas [36] and the rule-based processing of the stimulus situation mediated via prefrontal circuits and associated top-down processes (e.g., Refs. [20,49,57,82,105]). What then regulates the activation of the cortical cholinergic input system in such situations, thereby facilitating attentional performance?

In general terms, the limbic and cortical afferent projections of basal forebrain neurons ‘provide’ information about the behavioral significance of stimuli based on previous experience, motivation, and behavioral context [91]. This hypothesis has been extensively substantiated with respect to basal forebrain afferent projections arising from nucleus accumbens; furthermore, the available literature indicates close interactions between amygdaloid–accumbens circuits [23,34] which, collectively, ‘import’ information about the motivational and affective quality of stimuli to basal forebrain neurons [89]. Such afferent information is integrated in the basal forebrain with the converging input from the prefrontal cortex [107] that, as discussed above, recruits basal forebrain corticopetal projections as a component of the top-down regulation of neuronal systems mediating attentional performance.

The attentional effects of excitotoxic lesions of the mPFC, that is lesions which destroy the efferent projec-

tions of this area, provide initial insight into the functional power of such top-down processes. Obviously, the effects of such lesions go beyond specific attentional consequences and include a wide range of fundamental behavioral and cognitive impairments, particularly executive functions (e.g., Refs. [20,60,80]). In animals tested in the same sustained attention task that was used to deduce the role of cortical cholinergic inputs (above), excitotoxic lesions of the mPFC resulted in robust impairments in performance which did not specifically reflect impairments in sustained attention but indicated a randomization of response selection, reflecting a disruption of fundamental executive processes. Moreover, the lesioned animals’ performance was insensitive to the effects of a distractor [57]. Thus, the neuronal circuits that are *selectively* mediating sustained attention performance may be restricted to the cortical cholinergic input system and its afferent sources, as already concluded above. The top-down processes mediated via frontal efferent projections clearly are crucial for proper sustained attention performance, but their integrity is not exclusively important for sustained attention performance. To the extent that the attentional effects of activation of cholinergic inputs to the mPFC, or of cholinergic deafferentation of this area, can be interpreted in terms of ACh-dependent top-down processes, such processes may be more restricted than those deduced from the attentional effects of excitotoxic lesions of the mPFC, and they may function specifically to cope with the increased demands on sustained attention performance caused by distractors.

The enhanced processing of information in sensory cortical areas represents an interaction between the top-down regulation of these areas by the ‘anterior attention system’ and the direct effects of ACh in the cortex. Activation of cortical cholinergic inputs mediates two synergistically interacting processes, namely the activation of the ‘anterior attention system’ and thus the activation of the top-down functions of this system and the enhancement of sensory information processing in sensory and sensory-associational areas via activation of cholinergic inputs (see Fig. 1). As activation of the basal forebrain corticopetal cholinergic system itself is conceptualized as a component of the top-down processes, it is important to understand that there is no evidence in support of a sequential recruitment of the PFC and basal forebrain; rather, the close interactions between prefrontal regions and the basal forebrain, based anatomically on a closed-circuit (above), necessarily mediates the activation of the ‘anterior attention system’. The exception from this hypothesis are situations in which arousal-induced attentional processes (e.g., by stressful or anxiogenic stimuli; [4]) are mediated ‘bottom-up’ by LC ascending projections to recruit forebrain attentional circuits (above). In such situations, the basal forebrain corticopetal cholinergic projections may mediate the activation of the prefrontal cortex to trigger attentional processing (see also Ref. [94]).

In the aggregate, the ACh-mediated effects in the cortex facilitate the subject's readiness to monitor source(s) of signals, to detect such signals even if they occur rarely and unpredictably, to initiate the cognitive processes that result in a decision for, and the execution of, a response that indicates detection and processing of a signal, and to filter distractors. The data by McGaughy et al. [50] further substantiate this conceptualization as lesions of cortical cholinergic inputs selectively impaired the animals' ability to detect signals but not to reject non-signals. The rejection of non-signals does not depend on ACh-mediated enhancement of converging sensory inputs and thus, this measure does not reveal the absence of the interactions between ACh-activated top-down processes and ACh-facilitated sensory processing in lesioned animals. Conversely, such lesions disrupted the detection of signals because this required the ACh-mediated enhancement of sensory inputs, which was disrupted by the lesion.

The model illustrated in Fig. 1 also predicts that loss of cholinergic inputs that is restricted to the primary and secondary visual cortical areas does not suffice in impairing visual sustained attention performance [37]. To reiterate, the present model stresses that sustained attention performance depends on the interactions between the ACh-induced enhancement of sensory input processing throughout all levels of cortical input processing and the ACh-mediated recruitment of top-down processes via frontal cortical regions. Thus, restricted lack of ACh-mediated enhancement of primary and secondary visual input processing, although clearly affecting the neurophysiological correlates of visual information processing [32,43,90,106] would not be expected to affect sustained attention performance. The absence of attentional effects of infusions of the cholinotoxin 192 IgG-saporin into the primary and secondary visual cortex [37] also supports the notion that performance in such a task cannot be attributed solely to the ACh-mediated enhancement of the primary processing of sensory stimuli serving as targets in this task.

Finally, the prevailing focus on the cholinergic system in sustained attention should not be confused with the suggestion that sustained attention would be 'localized' within this neuronal system. Rather, the anatomical and electrophysiological characteristics of this neuronal system make it an ideal mechanisms for gating information processing in the entire cortical mantle [56]. Thus, in terms of localizing sustained attention, sustained attention is more adequately described as being mediated via the activation of the cortex by cholinergic inputs, specifically of anterior-parietal circuits, and the interactions between the modulation of sensory processing by the top-down processes, including the recruitment of interhemispheric circuits, the direct cholinergic stimulation of sensory areas and thalamic input to these regions (Fig. 1). Thalamic inputs import sensory information and, when activated via noradrenergic afferents, contribute to the induction of 'arousal' that is a prerequisite for proper attentional

performance (above). Thus, sustained attention is a function based on distributed, parallel circuits, with the cortical cholinergic inputs representing a crucial link in the mediation of sustained attention.

## 5. Ascending noradrenergic projections: the 'arousal' link?

The basis for the conceptual dissociation between sustained attention and arousal is stressed above. In support of this dissociation, the findings from functional neuroimaging studies have suggested that the neuronal circuits mediating the necessary arousal for proper sustained attention performance differ from those correlated with sustained attention. Specifically, the arousal components may be mediated via activation of the thalamus. Attentional performance-associated increases in thalamic activity were observed under low arousal conditions, possibly reflecting the mechanisms mediating the increased attentional effort required to perform the task under low arousal conditions ([72], see also the discussion in Ref. [13]).

Although noradrenergic projections originating from the locus coeruleus (LC) have been traditionally considered to mediate increases in arousal and aspects of attentional processing, their specific roles in sustained attention and arousal, respectively, have remained less well defined. Psychopharmacological studies in humans and in animals traditionally did not dissociate between arousal and attention when interpreting the effects of systemic manipulations of noradrenergic neurotransmission, particularly the effects of the administration of the  $\alpha_2$  receptor agonist clonidine. However, the findings from more recent studies support the hypothesis that rather than mediating specific attentional functions, ascending noradrenergic projections regulate the more general activation or arousal of the forebrain that is required for proper sustained attention performance [15,72]. Such a noradrenergically-mediated role in attentional performance may be attributed primarily to thalamic mechanisms. Coull and co-workers demonstrated that the administration of clonidine in humans performing a rapid visual information processing task resulted in the reduction of thalamic activity at baseline but not during performance [13–15]. The data from these studies collectively support the hypotheses that the attentional effects of clonidine depend more on the state of arousal than revealing a primary noradrenergic component mediating sustained attention, and that thalamic circuits mediate the interactions between arousal and attention (see also Ref. [69]).

Aston-Jones et al. developed a comprehensive model of the noradrenergic contributions to attentional processes. Based largely on the sympatho-excitatory afferents of the LC, noradrenergic projections are proposed to serve as the cognitive limb of a 'rapid response system' acting 'bottom-

up' to recruit telencephalic systems mediating attentional processes [2]. For example, the privileged attentional processing of fear- and anxiety-related stimuli has been theorized to depend on the noradrenergic activation of basal forebrain corticopetal projections [4]. Evidence in support of a regulation of the LC excitability by the prefrontal cortex indicates that even in such situations, bottom-up processes do not act in an isolated fashion but are subject to 'top-down' control [40]. Collectively, this hypothesis suggests that attentional functions are triggered, but not mediated, by noradrenergic ascending activation, and that sustained attention performance may not critically depend on variations in activity in ascending noradrenergic projections (see also Ref. [77]). This hypothesis is also supported by the results from several studies indicating that the ascending noradrenergic system does not crucially mediate attentional performance unless the state of arousal is manipulated by the presentation of salient, novel, or stressful stimuli [5,9,28,51].

## 6. Relationships with other forms of attention

Given the close theoretical relationships between different aspects of attention (sustained, selective, divided), it should not come as a surprise that the available data from neuropsychological, functional imaging, and animal experimental studies already suggest extensive overlaps in the circuits mediating different aspects of attention (e.g., Refs. [1,6,8,10,13,42,59,99,101]). For research purposes, it is important to maintain clear definitions of the aspects of attention studied. However, with respect to real-life performance, and to the underlying brain mechanisms, those differentiations may be of more limited significance. Monitoring a particular source of information requires, at the same time, the selection of such a source and the rejection of competing sources, and the allocation of processing resources to this task. Obviously, such tasks cannot be performed without mnemonic processing, taxing additional executive functions. Likewise, impairments in attention are difficult to be conceived as remaining restricted to a particular aspect of attention, particularly as such impairments escalate and affect all cognitive abilities [88]. Thus, the present reductionist attempt to determine the neuronal circuits mediating specifically sustained attentional functions represents a first step toward a more comprehensive understanding of the multiple circuits that allow us to effectively attend to our internal and external environment.

## 7. Major unresolved issues

The hypotheses that the activation of the fronto-parietal areas observed in humans performing sustained attention tasks reflects in part the consequences of cholinergic

stimulation of these regions is attractive but remains unsubstantiated. The present model predicts more widespread areas of cortical activation than reported in most of the available studies, although the relatively selective activity changes reported in those studies may in part be due to the methods used to isolate regions of interest in such studies [85]. Furthermore, the predominant role of the right hemisphere for sustained attention observed in human studies has not been addressed in the animal experimental literature on the functions of cortical cholinergic inputs. Right cortical lesions produce a more severe sensory neglect in humans and rats than left lesions [44,55], and lateralized cortical muscarinic receptor densities have been reported [70], raising the possibility that the prominent right hemispheric involvement in sustained attention is associated with lateralized cholinergic function [7]. It is also possible that in patients with lateralized lesions, sustained attention performance involves greater demands on alertness and thus on ascending noradrenergic activity. To the extent that noradrenergic inputs to the cortex are asymmetric and right hemisphere-dominant, patients with lesions in right fronto-parietal areas would be more susceptible to attentional challenges [73,81]. Alternatively, evidence in support of a cortical lateralization of sustained attention may be associated with the type of tasks used. This speculation predicts that spatial, non-verbal sustained attention tasks by default foster the demonstration of right hemispheric dominance in the mediation of sustained attention. As radiotracers for the visualization of presynaptic cholinergic activity and muscarinic and nicotinic receptor stimulation are becoming available for human SPECT and PET studies (e.g., Refs. [45,61,64]), future experiments will be capable of testing the hypothesis that sustained attention performance is associated specifically with increases in cholinergic transmission in the cortex.

## 8. Conclusions

Sustained attention represents a fundamental component of the cognitive capacities of humans. Aberrations in the ability to monitor significant sources of information rapidly develop into major cognitive impairments. Human neuropsychological and functional imaging studies have pointed to fronto-parietal areas, particularly in the right hemisphere, as being prominently involved in the mediation of sustained attention, or vigilance. Animal experimental evidence strongly supports the basal forebrain corticopetal cholinergic projection as a major component of the neuronal circuits mediating sustained attention performance. Activation of corticopetal cholinergic projections contributes to the recruitment of the anterior attention system and the associated top-down regulation of sensory and sensory-associational processing and, directly, enhances sensory input processing mediated via cholinergic projections to sensory cortical regions. These dual and interact-

ing functions of cortical ACh represent the crucial neuronal mechanisms mediating sustained attentional abilities. Future research will test these hypotheses in humans by using PET combined with radiotracers for markers of cholinergic transmission and muscarinic and nicotinic receptor function. Furthermore, animal models on the long-term attentional and cognitive effects of changes in cortical cholinergic inputs are needed. Finally, while hypotheses about the attentional consequences of loss of corticopetal cholinergic neurons or of decreases in cortical cholinergic transmission have been extensively studied, little is known about the long-term attentional consequences of pathological processes that are associated with abnormal increases in the (re)activity of cortical cholinergic inputs [88].

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### Effectiveness of an attention- training program

McKay Moore Sohlberg<sup>a</sup> & Catherine A. Mateer

<sup>a</sup> Good Samaritan Hospital, Puyallup, Washington

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## Effectiveness of an Attention-Training Program\*

McKay Moore Sohlberg and Catherine A. Mateer  
Good Samaritan Hospital, Puyallup, Washington

### ABSTRACT

Attention Process Training (APT), a hierarchical, multilevel treatment program, was designed to remediate attention deficits in brain-injured persons. The program incorporates current theories in the experimental attention literature. Four brain-injured subjects, varying widely in both etiology of injury and time post onset, underwent intensive cognitive remediation including 5 to 10 weeks of specific attention training. Results are displayed using a single subject multiple baseline across behaviors design. All four subjects demonstrated significant gains in attention following the initiation of attention training. Remediation of another cognitive function (visual processing) was not associated with alterations in attention behavior. The merits of a process-specific approach to cognitive rehabilitation are discussed.

Deficits in attention and concentration often go unrecognized or are misdiagnosed in the assessment of cognitive function following brain injury. Disruption of the physiological systems critical to the regulation of attention may occur as the result of seemingly minor, as well as severe, neurological damage. Deficits which initially present as memory impairments are often found to reflect underlying impairments in attention. Although the severity of an attention deficit nearly always lessens over the course of recovery, significant deficits in attention and concentration are often present many months or even years postinjury.

In the past, clinical models of attention have been largely restricted to the domain of asymmetries in spatial responsiveness or neglect. The experimental literature views attention in a somewhat broader framework, but this has not been tied in to clinical phenomena. In this study, a broadly based view of attention serves as the basis for the development of an attention-retraining program. Briefly, attention is conceptualized as the capacity to focus on particular stimuli over time and to manipulate flexibly the information. Examples of cognitive tasks which we feel are likely to reflect attentional deficits, based on our model, include: backward digit span, serial number sets, Trails B, and backwards spelling.

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There is far from universal agreement in the information-processing literature regarding the mechanisms of attention. Most models of attention are based on the human information-processing approach first introduced by Broadbent (1958). According to these models, attention is usually viewed as a selectivity phenomenon by means of which target stimuli receive priority processing over concurrent nontarget stimuli. That is, attention is considered to be the process by which one selectively responds to a specific event and is able to inhibit responses to simultaneous events (Johnston & Wilson, 1980).

Under the rubric of selectivity models there appear to be two basic classes of attention theory. The first class consists of the early-selection theories which are based on the view that the differential processing demands accorded target and nontarget stimuli operate at the perceptual level. Target stimuli are processed more fully because there is perceptual suppression of nontarget stimuli (Broadbent, 1958; Johnston & Wilson, 1980; Treisman, 1969). Brain mechanisms act to limit the amount of sensory input that an individual must process.

The second class of selective attention theories consists of the late-selection theories in which the differential processing accorded to target and nontarget stimuli is conceived of as being nonperceptual in nature. According to these models, a special attentional capacity within the organism allows for preferential processing of target stimuli over concurrent nontarget stimuli. All perceptual information enters the system, but only that which is selected by the special attention mechanism reaches higher processing centers (Johnston & Wilson, 1980; Shiffrin & Schneider, 1977). Hence, the basic difference between early- and late-selection theories lies in their view of the processing stage at which unimportant aspects of information or stimuli are screened out. The early-selection theories propose that certain stimuli are never processed due to perceptual suppression of nontarget stimuli; whereas late-selection theories propose that the unimportant information enters the system but simply is not chosen for further processing.

A shortcoming of the selectivity models is that they often stop at the level of signal detection or target selection. Additional processing of information tends not to be addressed in these theories. We feel a more comprehensive view of attention is necessary to adequately describe the attention deficits observed in brain-injured populations.

The theoretical construct of working memory as described by Baddeley (1974, 1981) does begin to address the comprehensive nature of attention. The Central Executive, one component of Baddeley's model, is hypothesized to provide for temporary storage of information. The capacity for such temporary storage allows for division of attention during information processing. Modeled as a controller of memory, the Central Executive allows information to be held in short-term storage while attention is temporarily shifted to other stimuli. This model thus incorporates additional levels of information processing.

The problem with all of the current models of attention, however, is that none adequately addresses the clinical phenomenon of attention deficits or their

remediation. The few treatment programs for attention which do exist tend to be task oriented without a strong theoretical base. At best, treatment programs address restricted components of attentional requirements. The purpose of the current study was to develop a clinical treatment program which considered attention to be a comprehensive and multilevel functional process.

### **Treatment Model**

The attention treatment program outlined in this paper was based on the experimental attention literature, clinical observation, and patients' subjective complaints. It considers attention as a multidimensional cognitive capacity. There are five levels of attention addressed in the therapy model: Focused Attention, Sustained Attention, Selective Attention, Alternating Attention, and Divided Attention. Descriptions of each level of the model are provided below.

*Focused Attention:* The ability to respond discretely to specific visual, auditory, or tactile stimuli.

*Sustained Attention:* The ability to maintain a consistent behavioral response during continuous or repetitive activity.

*Selective Attention:* The ability to maintain a cognitive set which requires activation and inhibition of responses dependent upon discrimination of stimuli.

*Alternating Attention:* The capacity for mental flexibility which allows for moving between tasks having different cognitive requirements.

*Divided Attention:* The ability to simultaneously respond to multiple tasks.

This paper examines the effectiveness of an attention-training program based on the model as described. Hierarchies of treatment tasks were developed for each of the five levels of the attention model. Therapy was conducted using tasks and treatment materials as outlined in Attention Process Training (APT) (Sohlberg & Mateer, 1986).

Outcome data is presented using a multiple baseline across behaviors replicated across four subjects (Hersen & Barlow, 1976). In this study, the Paced Auditory Serial Addition Task (PASAT; Gronwall, 1977) was used to evaluate attentional skills. This measure was chosen as the dependent variable for this study because of its demonstrated sensitivity to postconcussional attention deficits, its strong normative base and its inherent test-retest reliability (Gronwall, 1977; Gronwall & Wrightson, 1968). The PASAT reportedly provides an estimate of the subject's ability to register sensory input, rapidly process the information and respond verbally, as well as retain and use a complex set of instructions. In terms of the attention model described herein, the PASAT presupposes the existence of the first of the five levels (focused attention) and depends heavily on the adequacy of sustained and selective attention.

### **Design Considerations**

A multiple baseline across cognitive areas (Hersen & Barlow, 1976) was used to assess the effectiveness of the attention treatment program described in this

study. Previous research (Gianutsos, 1981; Gianutsos & Gianutsos, 1979; Gianutsos & Gianutsos, in press) has established the practicality of using the single-case design to study the retraining of cognitive processes in individuals.

In psychological research, the standard method of demonstrating significant change involves the analysis of group statistics to determine the probability of observed effects having occurred by chance (Bailey & Bostow, 1977). Typically, a large number of subjects are studied for a short period of time. This approach, however, is often not satisfactory for examining the changes in cognitive processes since the statistical manipulation of group data is likely to obscure changes in individual functioning. This is especially true for populations which display as much diversity in degree and nature of cognitive disability as brain-injured persons. Hence, single-case designs are being used with increasing frequency to study treatment effects in individuals.

The goal of the present study was to examine the relationships between the implementation of an attention-training model and changes in attentional skills as measured by the PASAT. To establish a functional relationship, it was necessary to observe changes in attention and plot improvement over time. Use of a multiple baseline design in which simultaneous changes in a second cognitive process area (i.e., visual processing) would be followed allowed us to formulate the following hypotheses:

- (1) An increase in PASAT scores over baseline levels will be observed following attention training;
- (2) Increases in PASAT scores following attention training will be maintained beyond the cessation of attention treatment;
- (3) Training of attention skills will not be associated with a generalized improvement in cognitive abilities. Attention training will not, for example, consistently result in changes on measures of visual processing;
- (4) Training of other cognitive processes, for example visual processing, will not regularly impact attentional skills.

## METHODS

### Subjects

The subjects were all participants at the Center for Cognitive Rehabilitation, a post-acute, day treatment brain-injury program. They were randomly selected from a consecutive series of admissions to the program. Subjects varied widely in both nature of injury and time postonset. Descriptions of demographic and neuropsychological data are presented for each subject in Table 1.

At the time of the program entry, each subject underwent a 2-week comprehensive cognitive and psychosocial evaluation including assessment of attention, visual processing, memory, and reasoning. Results from the testing were then used to determine which cognitive processes should be addressed and at what level of difficulty.

Table 1

Subject	01	02	03	04
Age	30	29	28	25
Sex	M	M	M	M
Education (years)	13	12	12	11
Time Post Onset (months)	14	72	12	48
Etiology	Aneurysm	Gunshot	Closed-Head Injury	Closed-Head Injury
Coma Duration	7 weeks	24 h	5 weeks	2 weeks
Preinjury Vocational Status	Owned an auto repair shop	Diesel mechanic	Dispatch controller	Flagman
VIQ	82	87	80	80
PIQ	74	98	88	88
FSIQ	77	85	82	82
Wechsler Memory Scale I				
<i>Paragraph Recall</i>	16/10	13/13	8/2	8/7
Immediate/delayed				
<i>Design Reproduction</i>	4/0	8/8	13/6	7/6
Immediate/delayed				
Digits (F/B)	5/3	5/4	6/5	6/5

### Measurement

The PASAT was administered in standard fashion using a tape made in accordance with the parameters set forth by Gronwall (1977). Subjects listened to an auditorially presented string of digits; they were required to add each number to the one immediately preceding it. Each score represented the percentage of correct responses made prior to the presentation of the next stimulus. Different norms were used for the first and later administrations of the PASAT (Gronwall, 1977).

Each subject was tested individually. All four subjects met criteria on two recorded pretest measures requiring repetition of 10 single digits and correct responses to 10 paced simple addition problems. This was followed by the administration of one practice list of 10 single digits recorded at 2.4-s intervals. Each full test trial consisted of 61 digits (numbers 1 to 9 used in random order). The interstimulus interval was always 2.4 s. A commercial tape recorder with intensity level well above threshold and adjusted to comfortable listening level in free field conditions was used.

The measure used to assess visual processing abilities was the Spatial Relations Subtest (SR) from the Woodcock-Johnson Psychoeducational Battery (1977). This is a test of spatial perception and judgment which requires the subject to identify discrete spatial components which would fit together to form the whole target figure. Scores on both the PASAT and SR test were obtained at regular intervals over the course of 30 weeks.

### Procedures

For each subject, a significant impairment in attentional skills and visual processing ability was identified. During the evaluation stage, at least two measures of PASAT performance were obtained. Scores achieved during this period, throughout which no treatment took place, served as the baseline. Subsequent to the evaluation, baseline

period, training in attention was initiated using the attention treatment model as described in this paper. Once subjects met individually determined criterion levels for the specific treatment tasks in each of the five levels of the attention-training model, remediation of visual processing skills was initiated. To control for an order effect, the above sequence was reversed for one subject (04), who received training in visual processing prior to attention training.

At least eight measures of performance on the PASAT and SR were taken with a minimum of two measures during each of the treatment phases (before, during, and after attention training). The subjects received between seven and nine individual cognitive retraining sessions per week which focused specifically on attention, visual processing, or memory, according to the treatment phase (see Figure 1). Each subject received 4 to 8 weeks of attention training, the length of training determined by the severity of attention deficit. Within that period, goals were set which provided maximal achievement within each of the components of the attention-training program. In addition to cognitive remediation each subject received concurrent intervention in the areas of daily living, prevocational, and psychosocial skills.

Treatment tasks were developed for each of the five levels of attention. Tasks were arranged in hierarchies of difficulty based on both the complexity of the tasks and processing speed requirements. It is important to recognize that at every level of the treatment model, success can be impaired by a slowed rate of processing or latency of response. A variety of computer programs, commercially available attention tasks and original treatment materials were adapted for use in each of the five levels of the attention model. A list of treatment tasks can be found in Appendix 1.

## RESULTS

Research findings for each of the four subjects are displayed using a multiple baseline across cognitive areas. Data for each subject are presented in a pair of vertically oriented graphs. The ordinate on the top graph represents PASAT z-scores used to measure changes in attention ability. Large intersubject variability prompted use of z-scores (as opposed to raw scores) in order to facilitate comparisons. The ordinate on the bottom graph represents raw scores on the SR used to measure changes in visual processing. The abscissa on both graphs corresponds to both weeks of treatment (lower scale) and the treatment phase (upper scale). Scores to the left of the heavy striped line represent the pretreatment baseline measures.

### Subject 01

Data for subject 01 (Figure 1) revealed a stable baseline for PASAT scores. Over the first 2 weeks during which no cognitive treatment had been provided, there was no change in PASAT scores. Following the initiation of attention training, PASAT scores increased from a z-score of  $-8$  to  $-1.4$ . This represents a dramatic increase in attention abilities as measured by the PASAT following specific attention training. Following cessation of attention training (during visual processing and memory training), scores remained at or above  $-2.2$  and

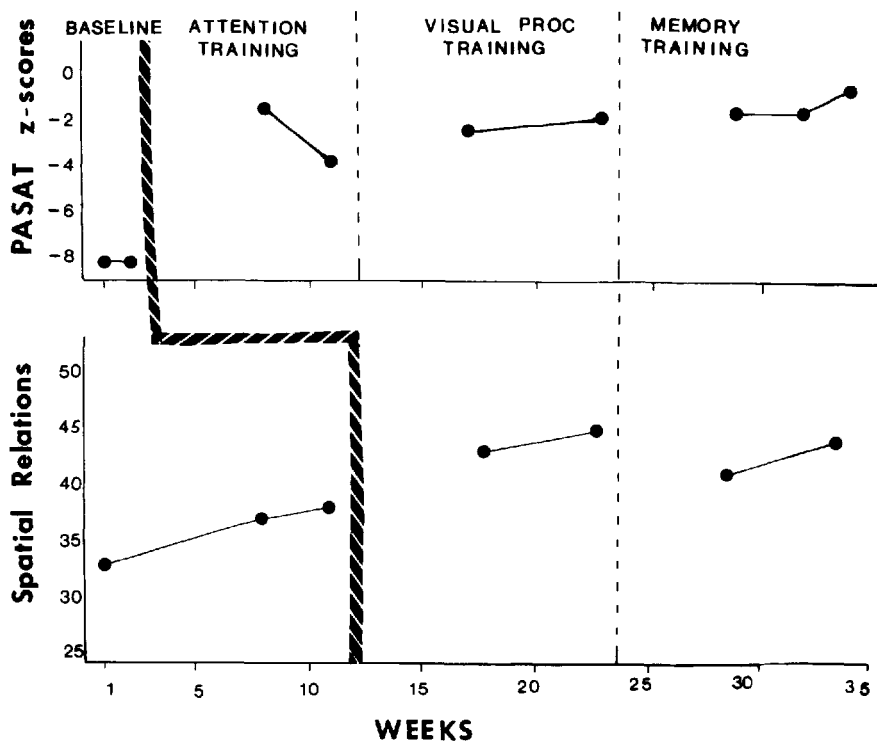


Figure 1. Results of attention training in Subject 01 using a multiple baseline across cognitive areas (attention, visual processing and memory).

showed a continuing gradual improvement. The baseline condition for the SR scores extended through the attention-training period since specific remediation in visual processing did not begin until the 12th week. During the baseline condition, there was a gradual improvement in SR scores in the absence of specific visual processing training. There is some suggestion, however, that SR scores may have been leveling off during this period. Following the initiation of specific visual processing training, SR scores increased significantly. With subsequent initiation of memory training, absolute SR scores decreased, yet remained above baseline.

At the time of program entry, this subject had been living with relatives during the 7 months since his discharge from the hospital. He was exhibiting profound cognitive problems and required 24-h supervision. The family had begun proceeding for psychiatric hospitalization due to a suicide attempt and unmanageable cognitive and behavioral disorders. He subsequently received 8 months of intensive cognitive training including 10 weeks of attention training. Following discharge, the subject began living independently in an apartment and obtained a paid half-time position as a food service worker. To date he has

maintained independent living status and been gainfully employed for 12 months.

### Subject 02

PASAT scores remained within .5 z-score standard deviation during the baseline condition (Figure 2). An increase in scores was noted following the initiation of attention training. After withdrawal of attention training, scores remained stable throughout visual processing and memory treatment phases (18 weeks). Scores on the SR task remained stable throughout the visual-process baseline period, despite provision of attention training. SR scores improved over the course of visual process training and remained high throughout the next cognitive process treatment phase.

This subject presented a particular challenge because of the long length of time postinjury. Upon program entry, he displayed moderate overall cognitive deficits, but exhibited marked impairments of initiation and executive functions due to extensive frontal-lobe involvement. He had been living with his parents

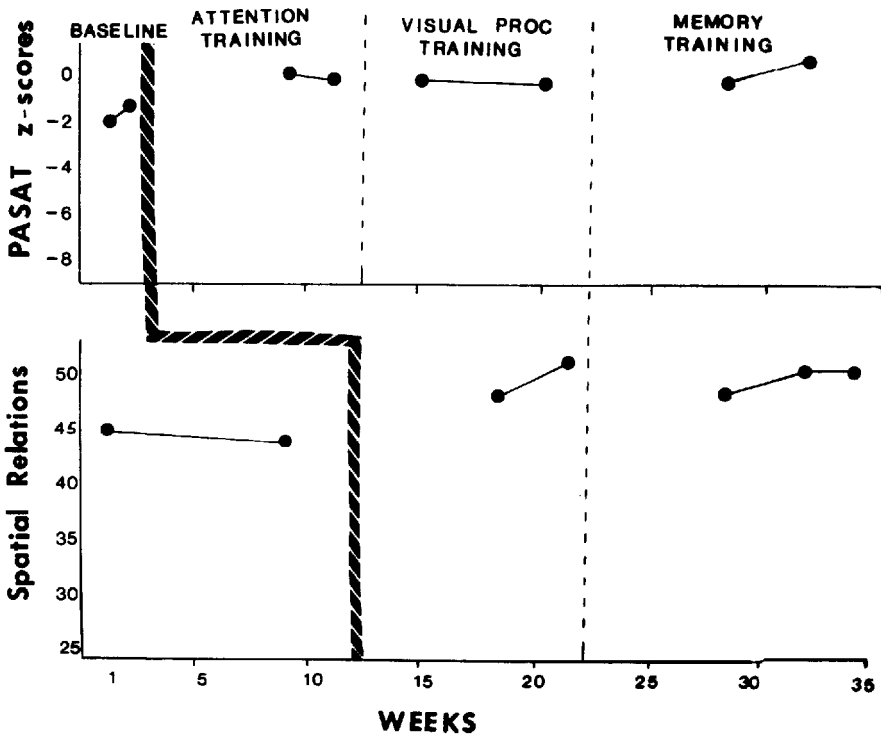


Figure 2. Results of attention training in Subject 02 using a multiple baseline across cognitive areas (attention, visual processing and memory).



during the 7 years since his injury. Despite the long period of time since injury, he made steady gains in many aspects of the cognitive program. Several perseverative and ritualistic behaviors, however, proved quite refractory to intervention. He received 10 weeks of specific attention training at the beginning of the program, achieving and maintaining normal range PASAT scores. Near the end of his program, he was involved in a successful transitional independent living trial, completed a work station experience in food preparation and was exploring several vocational retraining options. To the disappointment of staff, however, his parents terminated his program involvement prior to completion.

### Subject 03

This subject's PASAT scores were stable and just within normal limits during the pretreatment phase (Figure 3). Following attention training, scores increased and stabilized within the mid-range of normal expectations. SR scores also demonstrated remarkable stability not only prior to initiation of visual process training but over the period during which attention training was

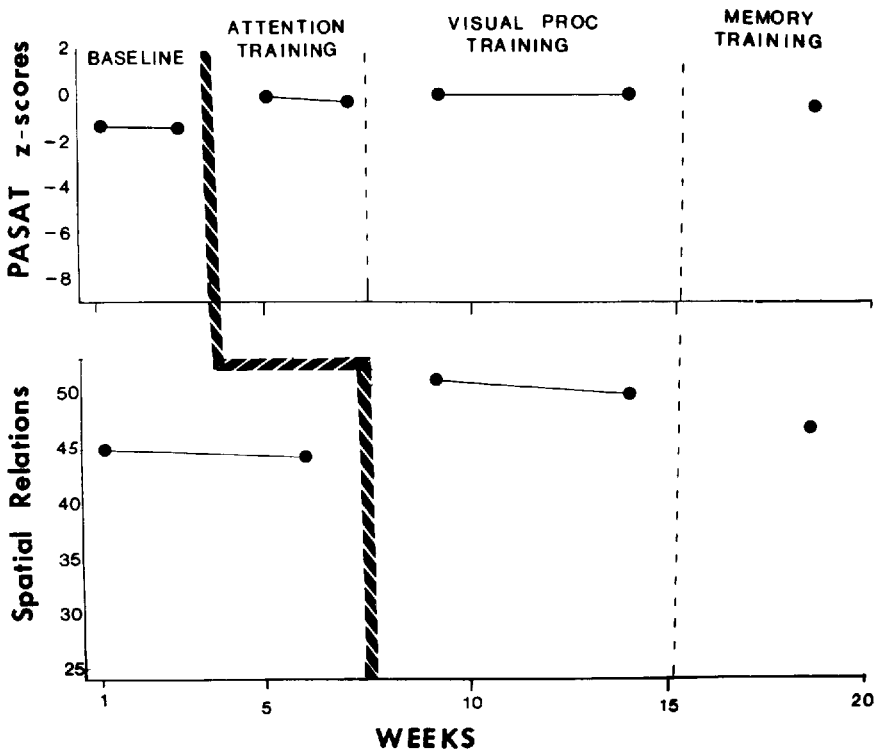


Figure 3. Results of attention training in Subject 03 using a multiple baseline across cognitive areas (attention, visual processing and memory).

proving effective in altering PASAT scores. SR scores only showed improvement during the period of intensive visual process training. Posttreatment SR data points gathered during the memory training phase regressed to pretreatment baseline levels.

At the time of program entry and during the initial 2 months of program participation, this subject resided in a full-care nursing facility. He required maximal assist for ambulation and many self-care activities, and demonstrated moderate generalized cognitive deficits. Attention training was not begun until 1 month after program entry, but he achieved normal range PASAT scores during the next month of specific attention treatment. During the program he moved from the nursing home to an independent apartment. Following program completion he returned to his former place of employment in a lesser capacity as a warehouseman for a magazine distribution company. He has been self supporting for 8 months at the time of this report.

#### Subject 04

To control for a possible order effect, the attention-training and visual-process-training periods were reversed in subject 04 (Figure 4). He received training in

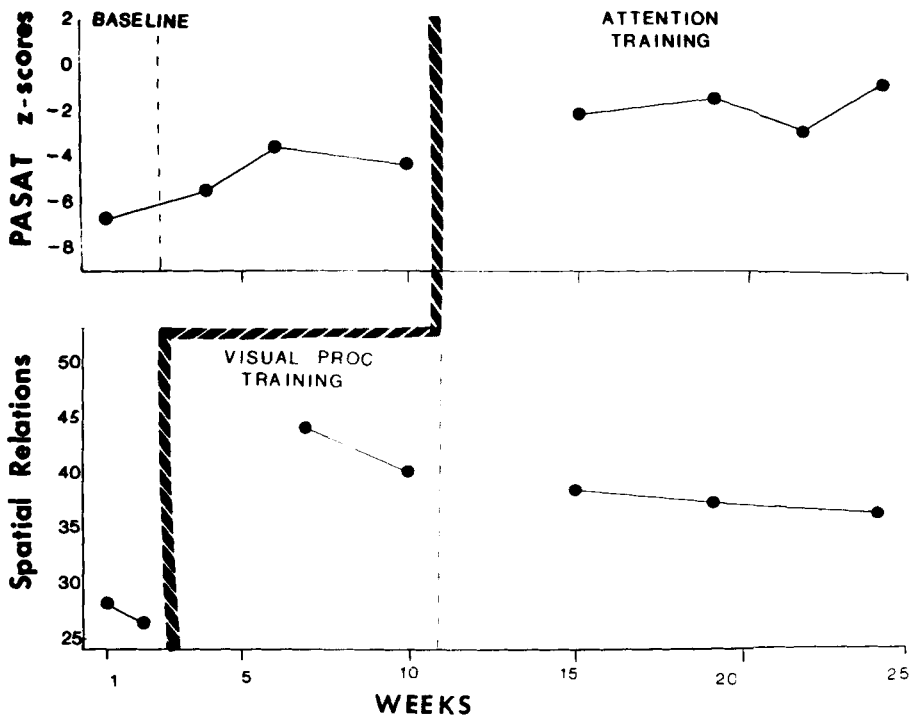


Figure 4. Results of attention training in Subject 04 using a multiple baseline (reversal) across cognitive areas (attention and visual processing).

visual processing prior to remediation of attention. Extremely poor scores characterized SR performance in the 3-week pretreatment period. Although dramatic improvements in SR scores were seen during the visual-process-training period, a slow but fairly steady decline was seen over the next 20 weeks. At the last testing, scores remained significantly above baseline levels, but were not judged to be stable. Scores on the PASAT did rise during the course of visual-process training in the absence of specific attention training, but leveled off over the 10 weeks at more than 3 standard deviations below expectations. In the period during and after attention training, PASAT scores showed improvement.

This subject, who was 4 years postinjury, had been living with his family and had participated unsuccessfully in several pain management programs prior to participation in the cognitive retraining program. He began attention training only after the baseline period and 10 weeks of very successful visual process training. The subject moved to independent living status during the program and 6 months following discharge he obtained employment as a printer.

## DISCUSSION

In the subjects who presented with mild to moderate attention deficits (02 and 03), indicated by PASAT scores within 2 *SD* of the mean, attention skills increased to within normal limits. The subjects with severe attention impairments (01 and 04), whose PASAT scores were greater than 3 *SD* below the mean, achieved scores within the mildly impaired range following attention training. Improvements in attention in all cases remained above baseline levels following cessation of specific attention training for periods as long as 8 months, which was the longest period of measurement. These results demonstrate the potential for improvement of attention deficits in brain-injured persons given specific attention training. They also support the general effectiveness of the attention-training model outlined in this study. We are as yet unable, however, to identify the relative contribution of individual components of the training program. We do not know, for example, whether it is critical to work on tasks within each of the five levels of our proposed hierarchy of attention. Nevertheless, the dramatic and sustained improvements in attention observed in all four subjects lend strong support for the provision of comprehensive attention training.

Models of cognitive rehabilitation generally fall into one of three major categories. These include the Functional Adaptation approach, the General Stimulation approach and the Process Specific approach. The Functional Adaptation approach facilitates functioning in a particular naturalistic living or work environment. This is commonly accomplished via task analysis followed by development of environmental manipulations or compensatory strategies. Problems arise, however, when the narrowness of focus and restricted generalizability of this model limit the potential extent of recovery. The General Stimulation

approach facilitates recovery through use of tasks which encourage cognitive processing at any level. The lack of theoretical orientation and poor accountability restrict the effectiveness of this model. A Process Specific approach to remediation, however, assumes the ability to differentially impact distinct cognitive areas. Treatment is oriented toward targeted remediation of deficits in specific cognitive areas.

Results in this study support the use of a process-specific approach to cognitive rehabilitation. The data suggest that, although there may be some impact on attentional skills following any focused cognitive treatment (i.e., visual processing), more significant improvements are made following specific attention training. In subject 04, gains in attention are evidenced during the baseline condition during which there was visual processing training but no specific remediation of attention. However, these gains appear to level off, and more dramatic increases are seen following specific attention training. In subjects 02 and 03, analogous results were found relative to visual processing ability. SR scores remained stable during the period of attention training, despite improved PASAT scores, and increased only after initiation of visual-process training. This double dissociation provides powerful support for independent improvements in specific cognitive areas. The clinical implication is that therapy directed toward remediation of underlying deficit processes should be encouraged.

A major problem inherent in many reports of cognitive treatment outcomes is the confounding of results by the training of assessment tools. The same task which is being used to assess an underlying behavior is used as the primary treatment task. In order to support a claim for having improved an underlying cognitive process, the change in criterion task (dependent variable) must not merely reflect practice effects or task familiarity. In this study, tasks and materials used in remediation of attention were developed in such a way that they simulated the general attentional requirements of the PASAT, but did not replicate the specific procedures. Therefore, observed changes in performance on the PASAT can be attributed to changes in attentional processing ability and not merely alterations in task performance.

We recognize that test scores on tasks such as the PASAT are not necessarily correlated with functional skills. Prior to program entry, none of the four subjects were living independently or gainfully employed. The clinical goals for each of the four subjects in this study included independent living (01, 02, 03, and 04) and sheltered employment (01 and 02) or competitive employment (03 and 04). In each case, vocational and independent living goals were achieved following 5 to 8 months in the program. Although we cannot attribute these outcomes solely to cognitive training, observed functional gains correlated in time with improvements in cognitive performance.

Although we feel the multiple baseline across behaviors design was useful for examining individual response to treatment, several problems with application of this design were encountered. This methodology requires repeated measurement of discrete, quantifiable behaviors. Currently, the best assessment of

cognitive behavior is through the use of neuropsychological tests. However, repeated test administration introduces problems related to practice effects. We attempted to deal with this problem by assessing performance more infrequently than is the case in most single-subject treatment designs and by using the established norms for first and later PASAT administrations. Additional data points in all phases of the study would have allowed more convincing evidence relative to performance trends.

In summary, results of this study confirm each of the four hypotheses regarding process-specific cognitive retraining. PASAT scores improved over baseline levels following attention training and remained significantly above initial performance throughout the period of postattention training measurement. Training of and improvement in attention skills was not routinely associated with improvements in visual processing abilities. Similarly, training of visual processing did not regularly impact PASAT performance. These results were interpreted as support for a process specific model of cognitive rehabilitation.

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## APPENDIX I

### Treatment Tasks Used in Attention-Training<sup>1</sup>

#### *Focused Attention*

REACT (reaction time computer programs published by Life Science Associates)  
 Attention Tape 1 (detection of auditorially presented number targets; developed by Sohlberg and Mateer, 1986)

#### *Sustained Attention*

Attention Tapes 2-8 (auditorially presented strings of stimuli with response requirements of increasing difficulty; Sohlberg and Mateer, 1986)  
 Serial Numbers (number manipulation exercises, Sohlberg and Mateer, 1986)  
 Timesense (time estimation computer program published by Soft Tools)

#### *Selective Attention*

Attention Tapes 9-16 (auditorially presented strings of stimuli recorded in background noise; Sohlberg and Mateer, 1986)  
 Visual Reaction Stimulus Discrimination 1 (computer program requiring inhibition of responses; published by Psychological Software Services)  
 Auditory Reaction Stimulus Discrimination (computer program requiring inhibition of responses published by Psychological Software Services)  
 Peg Board Exercises Using Noise Tape (visuomotor task with distractor)  
 Construx With Distractor Tape (visuomotor task with distractor)

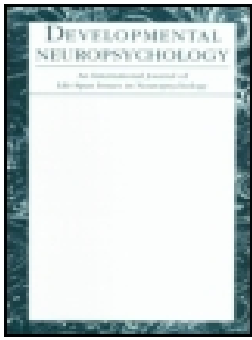
#### *Alternating Attention*

Addition/Subtraction Flexibility, Before/After, Odd/Even Number Flexibility (Sohlberg and Mateer, 1986)  
 Simultaneous Sequencing Exercises (Sohlberg and Mateer, 1986)  
 Set Dependent Activity I and II (Sohlberg and Mateer, 1986).

#### *Divided Attention*

Simultaneous Multiple Attention (computer program by Soft Tools)  
 Multilevel Card Sort (Sohlberg and Mateer, 1986)  
 React Plus Attention Tape (dual task, one requiring response to auditory information and another requiring response to visual information)

<sup>1</sup> Note: Materials referred to Sohlberg and Mateer (1986) are available as part of APT (Attention Process Training).



## A measure of children's attentional capacity

A. M. Weber & S. J. Segalowitz

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# A Measure of Children's Attentional Capacity

A. M. Weber

*Presbyterian Hospital  
Oklahoma City*

S. J. Segalowitz

*Brock University  
St. Catharines, Canada*

The Attentional Capacity Test (ACT; Weber, 1988) has been found to be a meaningful measure of attention in adults. This study explored the usefulness of this test with children. It was discovered that, with only minor modifications, this test could be administered to children; in addition the measure is resilient, in that it was not affected by background noise, sex, parental education, or conformity to mental counting instructions. It has been designed so that it can be used with speech and/or motor impaired people. ACT performance showed a strong association with age, improving across age levels until it reached an adult level by age 13. The preliminary normative data are presented here.

Attentional deficits are commonly alluded to in children with developmental learning disabilities and behavioral problems such as hyperactivity and conduct disorders and, more recently, have become a concern in children with acquired cognitive impairment due to traumatic head injury. Difficulties in attention often have a deleterious impact on the child's social, academic, and future vocational functioning. There has been considerable focus on researching the etiology and treatment of attentional disorders in children. However, in order to facilitate such endeavors, we need appropriate measures of attentional functioning in children that can both tell us about the normal development of attention and be sensitive to deviations from normative levels. Furthermore, children with attentional problems may differ from each other with respect to the nature of their deficit, depending on the aspect of their attentional ability that is defective (Kirby &

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Requests for reprints should be sent to A. M. Weber, Department of Neuropsychology/Brain Injury Rehabilitation, Presbyterian Hospital, Suite 601, 711 S. L. Young Boulevard, Oklahoma City, OK 73104.



Grimley, 1986). Obviously, we need specific measures of attention that will address the various components of attentional functioning.

One dimension of attention that has been repeatedly demonstrated as a key factor in the attentional problems of adults with closed head injuries and some other neurological conditions is that of how much information a person can attend to or process within a given time (see Mack, 1986; van Zomeren, Brouwer, & Deelman, 1984, for reviews, and see also examples by Ferris, Crook, Sathananthan, & Gershon, 1976; Miller, 1970; Miller & Cruzat, 1981; Stuss et al., 1985; Talland & Schwab, 1964). The term *attentional capacity* is synonymous with that of *information processing capacity* in the sense that the amount of information that can be attended to within a given time is the same as the amount that can be processed. The information attended to or processed may be internal, such as thoughts and memories, or external, such as sights and sounds. Reduction of this attentional capacity results in problems taking in information, slowness in mental processing, mental fatigue, and secondary emotional problems such as irritability, frustration, and depression.

Tasks that have been found to be sensitive in detecting deficits in attentional capacity include choice reaction time (Brouwer & Van Wolfelaar, 1985; Ferris et al., 1976; Gronwall & Sampson, 1974; Hart, Kwentus, Leshner, & Frazier, 1985; MacFlynn, Montgomery, Fenton, & Rutherford, 1984; Miller, 1970; van Zomeren, 1981; van Zomeren & Deelman, 1978), time to sort target cards from nontarget ones (Miller & Cruzat, 1981), divided attention tasks (Salthouse, Rogan & Prill, 1984; Stuss et al., 1985; Talland & Schwab, 1964), continuous performance tasks (Johnson, 1977; Kramer & Jarvik, 1979; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956), and the Paced Auditory Serial Addition Test (Gronwall, 1977; Gronwall & Sampson, 1974; Gronwall & Wrightson, 1974).

Although effective in measuring attentional capacity for clinical research purposes, these tasks tend not to constitute the sort of psychological measures that are suited to assessing the cognitive functioning of individual patients. That is, these tasks are often, at best, minimally normed and standardized, and have some further serious limitations for use with clinical populations:

1. They all require intact speech and/or motor response capacity, but many brain-impaired individuals cannot speak quickly or clearly and/or have slowed or restricted motor capacity.
2. Most of these tests are restricted in the range of attentional capacity that they measure. Optimal clinical use of attentional capacity measures requires their being suitable for monitoring a patients' progress or deterioration at both high and low levels of functioning.
3. Some of these tests are contaminated by requiring other skills such as arithmetic speed and accuracy.

The Attentional Capacity Test (ACT) was designed to overcome these problems. It can be used with people with motor and/or speech impairment, is not contaminated by other learned-skill factors, and can be used across a wide range of functional levels. It has been normed on young adults; its construct validity has been established in normals; and its predictive validity has been established in clinical populations (Weber, 1988).

This study was designed to explore the usability of the ACT with children and to answer the following questions:

1. Could the ACT tasks be done by children, and what administrative changes from the adult form need to be made?
2. How does ACT performance relate to age? It was expected that scores would increase across age levels.
3. Would ACT performance be affected by the sex of the child or by the level of parental education?
4. Would ACT performance be affected by moderate background noise of the level commonly penetrating walls in school and clinic settings?
5. Would the child's noncompliance with the instruction to count mentally (i.e., without visibly mouthing or audibly whispering) affect ACT performance? It was expected that younger children might have difficulty complying with this instruction.

## METHOD

### Subjects

The subjects were 72 children recruited from three elementary schools in the Lincoln School District of St. Catharines, Canada. There were eight 5-year-olds and 16 each of 7-year-olds, 9-year-olds, 11-year-olds, and 13-year-olds. For each age level, a child could be anywhere between one birthday and the next; for example, a 7-year-old could have had his or her seventh birthday that very day or be turning 8 the following day. Within each age group, half the subjects were boys and half were girls. All children were categorized as being average students, in that they had not been classified as either learning disabled or gifted. None of the subjects reportedly was on any psychotropic medications nor had been subject to any serious illness, change of residence or school, or major family change within the previous 3 months. English was the language in which these children typically engaged in any counting activity and, in all but one case, it was also the child's home language.

### Task

The ACT involves the processing of aurally presented numbers that are played on an audiotape recorder. The ACT has eight levels or subtests, and

TABLE 1  
Task Requirements of Each Level of the Act

<i>Level</i>	<i>Requirements</i>
1	Repeat single number.
2	Count number of "ee" sounds in a sequence of ee's.
3	Count number of 8s in a sequence of 8s.
4	Count number of 8s in a sequence of mixed numbers (i.e., the numbers 1 through 10 in random order).
5	Count number of 8s and 5s in a sequence of mixed numbers (one total).
6	Count number of 8s, 5s, 4s, and 7s in a sequence of mixed numbers (one total).
7	Count number of sequential pairs, 4-7 and 5-8, in a sequence of mixed numbers (one total).
8	Count numbers of sequences 5-number-8 in a sequence of mixed numbers. The number in the middle can be any number from 1 to 10 and it is possible to have overlaps between two such sequences if 5-5-8-8 occurs.

these are administered in a graded order from easiest to hardest. Before each level there are practice procedures to ensure comprehension of instructions. The child is told that the answer will always be between 1 and 10. The task requirements are summarized in Table 1.

At all levels, the onset of a trial is preceded by a double-buzz warning signal. For Levels 2 through 8, the end of a trial is denoted by a single buzz, that indicates it is time for the child to give his or her answer, that is, the total number of targets the child has counted. The demands of target discrimination are gradually increased although the speed of presentation (one stimulus per sec) stays the same. For Levels 4 through 8, the trial length and the number of targets stay the same.

### Procedures

Parental consent was obtained for all participants and parents also completed a brief questionnaire, which provided the information used to screen out children whose medication, recent life events, or linguistic background might have adversely affected their attentional functioning. Parents also indicated their own educational level on this questionnaire. Screening information designating students as average, and not learning disabled or gifted, was provided by the special education staff.

The ACT was administered individually to each child by the senior author, an experienced clinician and test administrator. The testing was conducted in a separate room in the child's school during regular class hours. The acoustical conditions of the testing situation varied according to what was happening in the nearby corridor or neighboring classrooms. The tester was more bothered by sudden increases in noise than the children appeared to be. They showed no outward reaction at all, remained on task, and were probably well habituated to such familiar noise fluctuations. However, in

case these noise variations did affect ACT performance, the tester recorded whether or not noise increased to a level that was distracting for her during each testing session.

The testing session lasted approximately  $\frac{1}{2}$  hr per child. The ACT was administered in the same way as is done for adults. The adult procedure, however, allows for flexibility during the practice phase that precedes each of the eight levels. It was this part of the administration that was modified where necessary, particularly for the 5- and 7-year-olds. However, similar modifications would also be appropriate for low-level adults. Modifications included the following:

1. Checking the one-to-one counting ability of all children in the 5- and 7-year-old groups and excluding those who did not demonstrate definite understanding of one-to-one counting to ten. Some 5-year-olds but no 7-year-olds were excluded on this basis. Tasks used were those of the child counting how many times the tester knocked on the table and counting circles drawn on a page.

2. As with the adult administration of this test, the children were instructed to count mentally, (i.e., without moving their lips or whispering). If necessary, extra demonstration and practice were given in mental counting. However, it was anticipated that younger children might not be able to cope with this requirement even with extra instruction. In such circumstances the child was allowed to continue in the study but record was made of whether they mouthed or whispered their counting.

3. The wording of instructions was simplified for younger children although the content was the same as that for adults.

4. During practice procedures more use of additional written-down examples was needed to convey the nature of the task than is usually needed with adults.

The total number of ACT trials is 24, and this number also constitutes the maximum possible "number correct" score. As with adults, testing was discontinued if the child scored zero on two successive levels but otherwise it continued through all items.

Children were asked not to divulge details about the test requirements to other students (so as to make it "fair" for everyone) until after the 3-week testing period was completed and, as far as could be ascertained, the children cooperated in this respect.

## RESULTS AND DISCUSSION

The analysis was designed to ascertain to what extent ACT scores were associated with the children's age, sex, and degree of conformity to the men-

tal counting instruction. The relationship of ACT scores to presence or absence of increased background noise and to parental education was also examined. Age was considered in terms of months of age. Conformity to the mental counting instruction was categorized as 0 for complete conformity, 1 for silent lip movements, and 2 for audible whispering. Parental education was examined for each parent separately and also multiplied together to give a combined rating. Educational level was categorized as 1 for Grade 11 or less, 2 for Grade 12, 3 for Grade 13, 4 for some or all of a college degree, and 5 for some or all of a university degree.

The seven variables (age, sex, noise, mental counting conformity, mother's education, father's education, and combined parental education) were each subjected to Pearson product-moment correlation with ACT score and the results are presented in Table 2.

Inspection of Table 2 shows that age, mental counting conformity, and mother's education were significantly correlated with ACT performance, whereas sex, noise, father's education, and combined parental education were not significantly related to ACT score.

Age was positively correlated with ACT score, older children scoring higher than younger ones, and this relationship accounted for 56.11% of shared variance. Sex did not account for a significant proportion of variance in ACT scores. Analysis of variance indicated that there was no sex by age interaction,  $F(4, 62) = 0.99, p = .42$ .

Mental counting conformity was negatively related to ACT performance, with less conformity being shown by poorer scorers than higher scorers. Further analysis indicated that this finding was really an artifact of age. Stepwise multiple regression analysis indicated that, although mental counting conformity accounted for a significant 9.70% of variance when entered first, it only accounted for .02% of variance when age was entered first. Age (56.11%) accounted for virtually all of the combined age/mental counting conformity variance (56.13%). That is, younger children tended to mouth or whisper their counting more than older children, who were better able to conform to the mental counting instruction.

Mother's education showed a negative relationship to ACT performance;

TABLE 2  
Pearson Product-Moment Correlations Between ACT Total Correct and Age, Sex, Noise, Mental Counting Conformity, Mother's Education, Father's Education, and Combined Parental Education

	<i>Age</i>	<i>Sex</i>	<i>Noise</i>	<i>MCC</i>	<i>Mother's Ed.</i>	<i>Father's Ed.</i>	<i>Combined Ed.</i>
Act Score	.75*	-.03	.08	-.31*	-.26*	-.07	-.17

\* $p \leq .05$  (two-tailed test).

Note. MCC = mental counting conformity; Ed. = education.

TABLE 3  
Means, Standard Deviations, and Ranges obtained  
by Normal Children and Adults on the ACT

	5 (n = 8)	7 (n = 16)	9 (n = 16)	11 (n = 16)	13 (n = 16)	Adults (n = 80)
M	8.9 (8.4)	11.6 (10.9)	13.9	14.9	18.3	18.6
SD	2.1 (1.7)	2.7 (2.4)	2.9	2.4	2.4	2.5
Range	6-12 (6-11)	7-16 (7-14)	11-20	11-19	13-21	13-23

*Note.* Range = total range of scores.

Adults: Data taken from Weber (1988). Age range 17-58 years, mean = 23 years, 90% = 32 years or younger. All were university students.

Figures in parentheses for 5- and 7-year-olds refer to the normative data for these younger age groups and assume administrative procedures that stop testing at the end of level 6 even if the other discontinue criterion has not been attained. Other data assume administration procedures that continue beyond level 6 if the discontinue criterion has not been reached.

mothers of poor scorers tending to be better educated than mothers of high scorers. However, this association also turned out to be an artifact of age. Stepwise multiple regression analysis showed that although mother's education accounted for a significant 6.96% of variance when it was entered first, it only accounted for a minute .04% when age was entered first. Age (56.11%) accounted for virtually all of the combined age/mother's education variance (56.15%). That is, mothers of younger children tended to be more educated than those of older children.

The main finding, therefore, is that ACT performance increases with age. Table 3 presents ACT mean scores, standard deviations, and ranges for each age group. It also provides adult data from another study (Weber, 1988) for comparison purposes. Figures in parentheses for 5- and 7-year-olds refer to an administrative modification for these younger children and should be used for clinical normative purposes (see later discussion).

Inspection of Table 3 indicates a certain amount of individual variation at each age level, some overlap between age levels, and a steady trend toward better performance with increasing age. By age 13, children are performing at the same level as adults. It seems that attentional capacity reaches a fully developed level by age 13 and that, subsequently, neither age (at least into early adulthood) nor education causes further development. Parental education does not seem to be a factor either, except insofar as more educated mothers were more prone to giving permission for younger children to be involved in the study than were less educated mothers. The test also seemed resilient in that performance was not affected by variations in background noise or by conformity with the mental counting requirement. Sex also did not significantly affect performance.

Generally, it was found that the adult form of administration for the ACT can be used with children, provided that simplified wording and extended practice procedures be used for children aged 7 or younger. The only major change required for children aged 7 or younger was with respect to the discontinue criterion. In this study, the criterion was the same as for adults (two consecutive levels with zero score), but it was noted that when this criterion permitted younger children to attempt levels 7 and 8, they had great difficulty comprehending the task requirements and an arduous time was spent on practice without any great increase in scores.

Because the omission of Levels 7 and 8 seemed clinically desirable for younger children, the data were examined to see whether such omission made any substantial difference to the resulting ACT scores. Among 5-year-olds, only three of the eight subjects scored correctly on items at Levels 7 and/or 8. If scores obtained at these upper levels were omitted from the total score, their mean score became 8.4, which was not significantly different from 8.9  $t(7) = 1.8708$ ,  $p > .05$ , and the range of their scores only decreased by 1 to that of 6–11. Among 7-year-olds, 8 of the 16 subjects scored correctly on items at Levels 7 and/or 8. When scores obtained at these upper levels were omitted from the total score, their mean score became 10.9, which was significantly lower than 11.6  $t(15) = 3.8954$ ,  $p < .01$ , and the score range decreased by 2 to become 7–14. However, for clinical purposes, it is the differentiation of individuals from each other that is important rather than absolute scores per se. Omission of Levels 7 and 8 makes the maximum possible ACT score 18 instead of 24. No 5- or 7-year-old child obtained a score beyond 16, so omission of the two upper levels for these younger children would not appear to endanger detection of individual differences through ceiling effects. Furthermore, within each of the two younger age groups, very high correlations were found between the condition where scores beyond level 6 were included in the total ACT score and the condition where the total score stopped at Level 6: 5-year-olds showed a Pearson correlation of .94 and a Spearman correlation of .90, and 7-year-olds showed a Pearson correlation of .96 and a Spearman correlation of .93.

For clinical purposes, it therefore seems appropriate to discontinue the ACT at the end of Level 6 for children aged 7 or younger if the standard discontinue criterion has not yet been reached. The figures in parentheses in Table 3 should be used for normative purposes with these younger children.

## CONCLUSIONS

The ACT appears suitable for use with children. For children aged 7 years or younger, this is true providing that the presence of one-to-one counting

ability to 10 is established, the test is not continued beyond Level 6, the wording of instructions is simplified, and extra practice and explanation are given as needed to ensure comprehension of instructions. These modifications have been incorporated into the standardized administration manual and may also have value for testing low-level adults. The test appears to be resilient in that performance does not appear to be affected by background noise, parental education, or conformity to mental counting requirements. It is also not affected by the child's sex. Further normative, reliability, and validity work is required before the test can be regarded as ready for everyday clinical use, but it is ready for research applications and some preliminary normative data have been presented.

Our findings strongly suggest that attentional capacity is fully developed by puberty and thereafter is not affected by age (at least into early adulthood) or education. It is likely that ACT performance declines as people enter older adulthood (Rabbitt, 1981, 1982), but this requires further exploration.

As stated in the introduction of this article, attentional functioning probably comprises a number of dimensions and the ACT has been designed to measure primarily a component that reflects the amount of information a person can attend to or process within a given time. Another important component is the person's ability to control and organize whatever attentional capacity is available, (i.e., the executive aspect of attention). The classifications in the *Diagnostic and Statistical Manual of Mental Disorders* (3rd ed.; American Psychiatric Association, 1980) and the revised version (American Psychiatric Association, 1987) of attention deficit disorder contain items that might reflect problems in either or both capacity and control. The ACT may well prove useful in clarifying one source of poor attention. If a child has deficits in attentional capacity, particularly of the auditory kind measured by the ACT, it could be expected that such a child would be overwhelmed by the normal pace of instruction in the classroom, have difficulty keeping up with ongoing conversations, lose track of stories and television programs, be slow at mental processing, be more readily mentally fatigued than his or her peers, require more breaks from ongoing tasks or activities, and generally find his or her efforts to keep up with peers a source of never-ending frustration.

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## Treating attention in mild aphasia: Evaluation of attention process training-II

Laura L. Murray\*, R. Jessica Keeton, Laura Karcher

*Department of Speech and Hearing Sciences, Indiana University, 200 S. Jordan Ave.,  
Bloomington, IN 47405, USA*

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### Abstract

This study examined whether attention processing training-II [Sohlberg, M. M., Johnson, L., Paule, L., Raskin, S. A., & Mateer, C. A. (2001). *Attention Process Training-II: A program to address attentional deficits for persons with mild cognitive dysfunction* (2nd ed.). Wake Forest, NC: Lash & Associates.; APT-II], when applied in the context of a multiple baseline ABA design, would improve the attention abilities of RW, a patient with mild conduction aphasia and concomitant attention and working memory deficits. We also explored whether APT-II training would enhance RW's auditory comprehension, other cognitive abilities such as memory, and his and his spouse's perceptions of his daily attention and communication difficulties. With treatment, RW improved on trained attention tasks and made modest gains on standardized tests and probes that evaluated cognitive skills related to treatment activities. Nominal change in auditory comprehension and untrained attention and memory functions was observed, and neither RW nor his spouse reported noticeable improvements in his daily attention or communication abilities. These and previous findings indicate that structured attention retraining may enhance specific attention skills, but that positive changes in broader attention and untrained functions are less likely.

*Learning outcomes:* As a result of reading this article, the participant will be able to: (1) summarize the previous literature regarding attention impairments and treatment approaches for patients with aphasia. (2) describe how Attention Processing Training-II affected the attention, auditory comprehension, and other cognitive abilities of the patient in this study.

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\* Corresponding author. Tel.: +1 812 855 3585; fax: +1 812 855 5531.  
E-mail address: [lmurray@indiana.edu](mailto:lmurray@indiana.edu) (L.L. Murray).

## 1. Introduction

Although aphasia has been traditionally defined in terms of impaired functioning in one or more language modalities (Benson, 1994; Grodzinsky, 1990), results from an increasing number of studies indicate that attention impairments commonly co-exist in chronic aphasia (e.g., Erickson, Goldfinger, & LaPointe, 1996; Kreindler & Fradis 1968; Murray, 2000; Tseng, McNeil, & Milenkovic, 1993). The construct of attention encompasses several basic and complex cognitive functions that enable selecting and manipulating external or internal stimuli for just a moment through to extended periods of time (Park & Ingles, 2001; Posner & Petersen, 1990). More basic attention functions include being alert enough to respond to stimulation and being able to sustain or maintain attention to a task or stimulus over time; complex attention functions allow us to switch rapidly our attentional focus and to respond simultaneously to multiple tasks or stimuli. In adults representing a spectrum of aphasia types and severities, both basic and complex attention functions have been found to be compromised, even when task materials are nonlinguistic in nature. For example, compared to healthy, non-brain-damaged peers, adults with aphasia perform less accurately, more slowly, or both on sustained attention (e.g., Korda & Douglas, 1997; Kreindler & Fradis, 1968), focused or selective attention (e.g., Cohen, Woll, & Ehrenstein, 1981; Van Mourik, Verschaeve, Boon, Paquier, & Van Harskamp, 1992), attention switching (e.g., Connor, Helm-Estabrooks, & Palumbo, 2001; Robin & Rizzo, 1989), and divided attention tasks (e.g., Erickson et al., 1996; King & Hux, 1996). Additionally, physiological differences (e.g., higher cortisol levels, longer latency and decreased amplitude of attention-related evoked potential waveforms) between healthy adults and those with aphasia have been identified during attention tasks (Laures & Odell, 2001; Peach, Rubin, & Newhoff, 1994).

Collectively, these findings have led to an attentional or processing model of aphasia in which some aphasic symptoms are proposed to be a product of or exacerbated by attention impairments (Connor, Albert, Helm-Estabrooks, & Obler, 2000; McNeil, 1997; McNeil, Odell, & Tseng, 1991; Murray, 1999, 2002). Several lines of research support this notion that attention deficits mediate language performance in aphasia. First, McNeil and colleagues (1991; McNeil & Doyle, 2000; McNeil & Kimelman, 1986) noted that purely linguistic accounts of aphasia insufficiently account for several prominent aphasic characteristics such as stimulability (i.e., manipulating extra-linguistic variables such as stimulus presentation rate (e.g., Brookshire, 1971) or visuospatial location (e.g., Coslett, 1999) influences the language abilities of patients with aphasia) and intra-subject variability (i.e., language performances in patients with aphasia regularly differ quantitatively and qualitatively across repeated administrations of the same task completed in the same testing context (e.g., Connor et al., 2001)). Second, significant correlations have been found between aphasic patients' performances of certain attention and language tasks (Petry, Crosson, Gonzalez-Rothi, Bauer, & Schauer, 1994). Third, as the attentional demands of language tasks are increased (i.e., in the presence of distraction; while completing a competing task), patients with aphasia demonstrate significant disruption in lexical-semantic and syntactic aspects of auditory processing (Murray, Holland, & Beeson, 1997a; 1997b; Tseng et al., 1993), and lexical-semantic, syntactic, and pragmatic aspects of verbal output (Murray, 2000; Murray, Holland, & Beeson, 1998) than

their non-brain-damaged peers. Lastly, attention appears to influence both language ability and recovery in patients with aphasia. For example, patients with concomitant cognitive deficits (including attention problems) have been found less likely to benefit from aphasia treatment than those patients without co-existing cognitive problems (Goldenberg et al., 1994; Murray, Ballard, & Karcher, 2004). Likewise, attention impairments appear to have a greater influence than degree of language deficits on the vocational outcomes of patients with aphasia (Ramsing, Blomstrand, & Sullivan, 1991).

Given the documented relation between attention and language in aphasia and the apparent detrimental effects of attention deficits on functional outcomes, several researchers have recommended directly treating attention to enhance indirectly these patients' language as well as other cognitive abilities (Goldenberg, Dettmers, Grothe, & Spatt, 1994; Murray, 1999, 2002; Van Mourik et al., 1992). Whereas many studies have evaluated attention training in patients with traumatic brain injuries (e.g., Cicerone, 2002; Sohlberg, McLaughlin, Pavese, Heidrich, & Posner, 2000), descriptions and empirical testing of attention treatments for adults with aphasia are thus far scant. An early exception is the work of Sturm and colleagues (1991; 1997). Utilizing a series of computerized tasks, these researchers found that their patients with aphasia or right hemisphere brain damage improved on the trained attention tasks; modest generalization to untrained attention domains, however, was observed only when the computer tasks were more "functional" (e.g., a photographic safari task in which patients pressed a key to take snap shots of certain objects, animals, or people) and when basic attention functions (e.g., arousal, sustained attention) were targeted. Although negligible generalization to other cognitive abilities (e.g., nonverbal problem solving) was found, the researchers did not evaluate language and so the effects of their treatment on this domain remain unclear.

In 2000, Helm-Estabrooks, Connor, and Albert used their Attention Training Program (ATP) to evaluate whether treating nonlinguistic aspects of cognition would enhance language in patients with chronic aphasia. ATP activities (e.g., symbol cancellation, auditory continuous performance) progress from relatively basic, sustained attention tasks to those with more complex, focused and alternating attention demands. Following approximately 2 months of twice-weekly therapy, two patients with mixed nonfluent aphasia displayed improvement on ATP tasks, as well as substantial gains in nonverbal reasoning and moderate, although still functional, improvement in auditory comprehension. Several months post-treatment, both patients had retained their nonverbal reasoning improvements, but their auditory comprehension gains had deteriorated. Similarly, Kohnert (2004) provided 2 months (i.e., 14 one-hour sessions) of cognitive treatment to a patient with chronic, transcortical motor aphasia. Cognitive activities such as card sorting, simple math computations, and visual search tasks were used to target sustained and alternating attention abilities. Post-treatment testing revealed substantial gains on all trained cognitive tasks, and moderate improvements in untrained language comprehension and production abilities. Definitive conclusions regarding the effects of these cognitive protocols cannot be rendered, however, until more detailed descriptions of these studies' procedures become available (e.g., treatment criteria were unspecified), and further investigations utilize more controlled, study designs (e.g., inclusion of a control test or probe to evaluate if improvements should be attributed to treatment versus other, nonspecific therapy variables).

Given the limited number of investigations concerning the potential effects of direct attention training on language recovery in aphasia, there clearly remains a need for further empirical research. Of particular interest is determining whether an attention treatment that incorporates linguistic stimuli might evoke greater and more enduring gains in language than those previously observed (e.g., Helm-Estabrooks et al., 2000; Kohnert, 2004). That is, given that previous cognitive protocols included primarily nonverbal, visual tasks, and that previous patients displayed greater gains in visual cognitive skills than language, it is possible that more remarkable language improvements might be achieved if treatment placed demands on both attention and linguistic abilities.

Currently there are two commercially available programs for remediating attention impairments via language-based tasks, Attention Process Training (APT; Sohlberg & Mateer, 1986) and APT-II (Sohlberg, Johnson, Paule, Raskin, & Mateer, 2001). These programs are based on a clinical model of attention in which attention consists of separable domains and is supported by several neural networks; thus, several aspects of attention will be most likely compromised following brain damage. Accordingly, both programs target a variety of attention functions (i.e., sustained, selective, alternating, and divided attention) via a series of graded activities, each of which is designed to isolate and stimulate a specific attention skill. The programs differ in that APT-II represents an upper extension of the original APT and therefore contains more demanding tasks to address the more complex attention impairments associated with relatively mild traumatic brain injuries (TBI).

Whereas some empirical research has evaluated these programs, these studies have exclusively involved TBI patients and additionally, have so far produced mixed findings. For example, Sohlberg, Mateer, and colleagues (Mateer, 1992; Mateer, Kerns & Eso, 1999; Sohlberg & Mateer, 1987; Sohlberg et al., 2000) conducted several investigations to explore the effects of APT on the attention and other cognitive abilities of patients with varying degrees of TBI severity. They consistently found that following APT, their patients displayed improvements on trained tasks and standardized attention tests (e.g., Paced Auditory Serial Addition Task; PASAT; Gronwall, 1977). More recently, positive effects on standardized tests and patient interviews designed to assess memory, learning, executive functioning, and levels of functional independence also were observed (Sohlberg et al., 2000). In contrast, Park, Proulx, and Towers (1999) reported that their patients with severe TBI achieved better PASAT performances following APT, but only nominal improvement on a memory test and no change on a depression measure; furthermore, their control group who was tested but not treated similarly showed gains on the PASAT but no improvement on the memory test. Park et al. concluded that APT facilitates only those specific attention skills targeted by treatment and does not foster improvement in other untrained attention and cognitive functions.

Only one APT-II study has been conducted to date. Palmese and Raskin (2000) provided three patients with mild TBI 10 h (1 h/week) of APT-II, and found that each patient demonstrated not only improved attention and processing speed on trained tasks, but also increased scores on the PASAT and two memory tests. Additionally, 6 weeks following treatment termination, the patients continued to display these improvements. Despite these encouraging findings, further evaluation of APT-II is needed to determine the reliability of Palmese and Raskin's results and to examine if positive effects generalize to patients' daily functioning and their perceptions of their impairments.

Accordingly, the present study was conducted to evaluate the following research questions:

- (a) Would APT-II treatment positively affect the attention abilities of a patient with chronic aphasia and co-existing attention and working memory problems?
- (b) Would attention improvements related to APT-II treatment evoke concomitant improvements in auditory comprehension and other aspects of cognition?
- (c) Would the patient and his spouse perceive improvements in his daily attention and communication skills subsequent to APT-II treatment?

## 2. Methods

### 2.1. Subject

RW is a 57-year-old, right-handed male who suffered a left embolic stroke in September 1996. A CT scan indicated left hemisphere damage to cortical and deep areas of his posterior temporal lobe and most of his parietal lobe, including supramarginal and angular gyri. Following his stroke, according to the *Aphasia Diagnostic Profiles* (ADP; Helm-Estabrooks, 1992), he presented with mild to moderate Wernicke's aphasia including moderately impaired auditory comprehension and repetition abilities, and mild to moderate anomia. RW has an engineering degree and was able to return to the job he held prior to his stroke.

RW was first evaluated at our university speech and hearing clinic in June 1997 and was subsequently enrolled in individual outpatient therapy. Since then, he has continued to receive individual therapy on a variable basis depending on his schedule (e.g., depending on demands at his place of employment). Additionally, since September 1998, RW and his spouse have regularly attended weekly Aphasia Support Group meetings. Previous therapy goals primarily focused on use of compensatory strategies to assist auditory comprehension (e.g., requesting repetitions, taking notes) and word retrieval abilities (e.g., providing circumlocutions or synonyms), and direct stimulation of his auditory comprehension (e.g., listening and answering questions about increasingly longer and more complex paragraphs) and writing skills (e.g., repetitive practice of report writing to increase writing speed and accuracy). Although RW demonstrated steady progress on all treatment activities, he continued to report (as did his wife) and display difficulty comprehending spoken language in daily, complex listening conditions (e.g., noisy environments, conversations with multiple communication partners, when complex and figurative language were used).

### 2.2. Pre-treatment assessment

Pre-treatment linguistic and cognitive testing was completed in November 2000 (see Table 1). RW passed pure tone hearing and depression screenings (Yesavage et al., 1983) indicating that neither basic auditory problems nor depression were likely contributors to his current linguistic or cognitive difficulties. On the ADP, RW displayed mild problems comprehending and producing concrete, spoken language, but greater difficulty with repetition and singing tasks; his language profile was consistent with conduction aphasia.

Table 1  
Pre- and post-treatment testing data for subject RW

Measure	Pre-treatment (November 2000)	Post-treatment (November 2001)
Aphasia Diagnostic Profiles	Standard score <sup>a</sup> (raw score)	
Personal information (24)	14 (24)	14 (24)
Writing (30)	15 (30)	15 (30)
Reading (30)	13 (30)	13 (30)
Information units	13 (14)	13 (15)
Phrase length	12 (12.4)	12 (12.0)
Naming (36)	13 (35)	13 (35)
Auditory comprehension (28)	12 (24)	13 (25)
Repetition (36)	9 (25)	9 (26)
Elicited gestures (21)	13 (21)	13 (21)
Singing (9)	7 (3)	7 (3)
Lexical retrieval	14	14
Aphasia severity	112 <sup>b</sup>	115
Aphasia type	Conduction	Conduction
Test of Language Competence	Standard score <sup>c</sup> (raw score)	
Ambiguous sentences (39 max)	8 (29)	9 (30)
Making inferences (36 max)	6 (28)	9 (32)
Recreating sentences (78 max)	5 (60)	5 (59)
Figurative language (36 max)	10 (32)	10 (32)
Communicative Effectiveness Index	mm (100 mm max)	
Spouse rating RW	66.8	68.1
RW's self-rating	68.0	69.2
Working memory task	Raw score	
Word recall errors (42 max)	25	21
True/false errors (42 max)	5	2
Wechsler Memory Scale-Revised	Percentile (raw score)	
Logical memory I	66 (27)	76 (27)
Logical memory II	53 (20)	53 (19)
Digit span		
Forwards	<4 (4)	5 (5)
Backwards	12 (4)	31 (5)
Visual Memory Span		
Forwards	73 (9)	81 (9)
Backwards	18 (5)	59 (7)
Visual reproduction I	94 (37)	98 (37)
Visual reproduction II	94 (36)	98 (37)
Test of Everyday Attention	Scaled Score <sup>d</sup>	
Map search (First minute)	7	8
Map search (second minute)	8	11
Elevator counting with distraction	10	12
Visual elevator (accuracy)	13	10
Visual elevator (timing)	8	10
Elevator counting with reversal	11	13
Telephone search	10	11
Telephone search while counting	7	14



Table 1 (Continued)

Measure	Pre-treatment (November 2000)	Post-treatment (November 2001)
APT-II Attention Questionnaire		
Spouse rating RW	25	23
RW's self-rating	29	26
Geriatric Depression Scale		
≥11 Indicative of depression	8	7

<sup>a</sup> Standard score with  $M = 10$ ,  $S.D. = 3$  based on a sample of 140 right-handed patients with left-hemisphere stroke.

<sup>b</sup> Standard score with  $M = 100$ ,  $S.D. = 15$  based on standardization sample of 222 stroke patients.

<sup>c</sup> Standard score with  $M = 10$ ,  $S.D. = 3$  based on standardization sample of 116 non-brain-damaged adolescents between the ages of 17–0 to 18–11.

<sup>d</sup> Scaled score with  $M = 10$ ,  $S.D. = 3$  based on a sample of 154 non-brain-damaged adults.

The *Test of Language Competence – Expanded Version* (TLC-E; Wiig & Secord, 1989) was given to evaluate RW's high-level language abilities (e.g., understanding inferred or implied material). To interpret his performance, his standardized scores were compared to norms for the TLC-E's oldest age group (i.e., 17–18 years, 11 months). According to these norms, he scored at or within one standard deviation (S.D.) of the mean on the ambiguous sentences and figurative language subtests, but below the mean for the remaining subtests. His TLC-E raw scores also were compared to those of healthy adults of similar age and/or educational background reported in previous studies (Chenery, Copland, & Murdoch, 2002; Lethlean & Murdoch, 1997). This comparison indicated that his raw scores on the ambiguous sentences and recreating sentences subtests consistently fell greater than two S.D. below the means reported in both previous investigations. Collectively, these findings indicated that at least some high-level language comprehension and production abilities were problematic for RW.

The communicative effectiveness index (CETI; Lomas et al., 1989) was used to determine RW's as well his wife's perception of his current communicative strengths and weaknesses. Both he and his spouse gave relatively similar ratings on most CETI items, and reported that he displayed most difficulty on the following items: "Being part of a conversation when it is fast and there a number of people involved," and "Getting involved in group conversations that are about him/her."

Several tests were used to evaluate RW's verbal and nonverbal memory and attention abilities. RW demonstrated significant difficulty on the auditory verbal working memory test (Tompkins, Bloise, Timko, & Baumgaertner 1994): The number of recall errors made by RW fell greater than two S.D. above the mean performance of Tompkins et al.'s control group ( $M = 6.4$ ,  $S.D. = 4.6$ ) and close to one S.D. above the mean of their left hemisphere group ( $M = 16.8$ ,  $S.D. = 10.8$ ). Results from logical memory and digit span subtests of the *Wechsler Memory Scales – Revised* (WMS-R; Wechsler, 1987) indicated deficits of immediate and delayed verbal recall, particularly when there was little contextual support (i.e., digit span). With the exception of his poor performance on backwards visual memory span, RW performed well above average on subtests that evaluated visual memory skills and had relatively low linguistic demands.

The *Test of Everyday Attention* (TEA; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994) was used to assess sustained, focused, alternating, and divided attention. RW displayed most difficulty on timed attention tasks regardless of whether they were linguistically loaded (i.e., visual elevator-timing, telephone search while counting) or not (i.e., map search). Although his scaled scores suggested only mild attention problems or within normal performance for his age group, they were interpreted to represent more significant deficits considering his and his spouse's subjective descriptions of his premorbid capabilities, and his educational and professional history; this interpretation of his performance was consistent with the TEA authors' recommendation to base clinical decisions regarding "abnormal" versus "normal" subtest performance on both scaled scores and premorbid abilities (see p. 12 of the TEA test manual).

Results from the APT-II (Attention Questionnaire) (Sohlberg et al., 2001) further established that RW demonstrated decreased attention skills compared to his premorbid status. Across the 12 items on the questionnaire, RW rated 1 as problematic "all the time" (i.e., "trouble paying attention to conversation, if more than one other person"), 3 as "frequently" problematic, 6 as "sometimes" problematic, and 1 as only occasionally problematic. His wife rated 3 items as frequently problematic, 8 as sometimes problematic, and only 1 as never problematic for RW. Both of them rated items pertaining to communicating under more demanding attention conditions as "frequently" problematic for RW (e.g., "Slow to respond when asked a question or when participating in conversations," "Miss details or make mistakes because level of concentration decreased").

In summary, RW presented with mild conduction aphasia with primary linguistic deficits in repetition, and high-level auditory comprehension and spoken language formulation. Additionally, he demonstrated working memory deficits, particularly for auditory verbal material, and mildly impaired attention with greater difficulty on timed tasks. Poor performance on cognitive tests did not simply reflect his linguistic limitations as he displayed difficulty on subtests that had both low (e.g., TEA map search) and high (e.g., auditory verbal working memory test) linguistic demands. Linguistic and cognitive test results were consistent with the subjective reports of RW and his spouse regarding the nature of his difficulties subsequent to his stroke.

Because previous, more traditional approaches to remediating RW's auditory comprehension deficits had been associated with only modest functional gains in his daily communication skills, because cognitive testing indicated concomitant attention and working memory problems, and because some initial aphasia research has suggested that treating co-existing cognitive deficits may enhance language skills (e.g., Helm-Estabrooks et al., 2000), we selected a cognitive approach to treat directly his attention and working memory difficulties, and hopefully, indirectly address his daily auditory comprehension problems. The APT-II program was selected because of (a) its clinical convenience, (b) its use has been associated with some positive outcomes for TBI patients (e.g., Palmese & Raskin, 2000), and (c) its tasks and organization are theoretically motivated (Sohlberg et al., 2001). That is, the clinical model of attention upon which the APT-II was developed is consistent with other attention theories as well as experimental and clinical evidence supporting the existence of distinct attention functions (Filley, 2002; Posner & Petersen, 1990). Sohlberg et al. (2001) also acknowledged the close interdependence between

working memory and attention (see also Kane, Bleckley, Conway, & Engle, 2001), and accordingly noted that certain APT-II tasks engage both working memory and attention; therefore, we hoped that APT-II would help RW strengthen both of these cognitive domains, which appeared problematic during pre-treatment testing. Lastly, we selected APT-II tasks that primarily stressed auditory attention because RW demonstrated and reported greater difficulty processing and responding to auditory stimuli, and because some attention models assert that separate attention resources support auditory and visual processing modalities (McLeod, 1977; Wickens, 1989).

### 3. Procedures

#### 3.1. Study design

A single subject, multiple baseline ABA design was used (Richards, Taylor, Ramasamy, & Richards, 1999). Auditory comprehension was regularly probed to determine if attention training was associated with concomitant changes in this language ability. During the treatment phase, RW completed APT-II activities that targeted auditory sustained, selective, alternating, and divided attention. The criterion for treatment termination was mastery of all targeted APT-II tasks (i.e., 90% accuracy over three consecutive trials for each task) or three semesters of training (i.e., approximately 10 weeks/semester), whichever occurred first. A rapid naming task served as a control probe because this task assessed a linguistic behavior anticipated to remain relatively unaffected by the auditory attention treatment (Wickens, 1989), but still involved certain attention skills (i.e., sustained and selective attention, albeit in the visual modality).

#### 3.2. Probe tasks

To monitor auditory comprehension, a paragraph listening probe was created (see Appendix A). This task required listening to four pre-recorded passages (approximately 3 min each), and then answering seven pre-recorded multiple-choice questions (four choices/question). Materials were modified from Graduate Record Examination practice items (Educational Testing Service, 1998) with passages approximating each other in length ( $m = 325$  words, range = 319–339 words), complexity (i.e., grade level 15; Fry as cited by Vacca & Vacca, 1989), and topic familiarity. In addition to response accuracy, response times (RT) were recorded for each question so that a mean RT for each passage and across passages could be monitored.

A rapid naming task (RAN) served as the control probe, and involved naming as quickly and accurately as possible for 2 min a set of pictured objects. Materials and procedures were adapted from those of Denckla and Rudel (1974, 1976), and consisted of pictured objects arranged on four large (11 in.  $\times$  14 in.), laminated sheets. Each sheet had 10 rows with 5 line drawings of common objects (Snodgrass & Vanderwart, 1980) randomly arranged within each row. Each set of 5 line drawings depicted 4 monosyllabic and 1 disyllabic words (e.g., glasses, leaf, saw, cake, sheep), with mean word frequency (Kucera & Francis, 1982) matched across sets.

Of the four stimulus sets developed for each probe task, three were randomly selected for administration throughout all experiment phases. During the treatment phase, one Paragraph and one RAN probe were administered at the beginning of each session, randomizing the order of probe tasks and stimulus sets across sessions. The remaining set of Paragraph and RAN probe stimuli was only used during pre- and post-treatment testing to assess for exposure effects. As recommended, all probe sets were administered three times during baseline (Fukkink, 1996). One week and 2 months following treatment termination, all probe sets were given to examine for maintenance of possible treatment effects.

### 3.3. Treatment

Treatment began with the most basic APT-II task that targeted auditory, sustained attention with the hopes of progressing through all auditory sustained, selective, alternating, and divided attention tasks (see Table 2). RW was provided 60 min weekly therapy sessions at the university clinic following procedures in the APT-II manual. Both RT and accuracy were recorded. RW also completed, depending on his schedule, 20–60 min per week of home practice. His spouse was extensively trained to collect accuracy and RT data during these at-home treatment sessions.

To move to a new APT-II task, RW was required to achieve 90% accuracy over three consecutive trials; although APT-II manual recommends one or no errors or false alarms on two consecutive trials (Sohlberg et al., 2001), a more conservative criterion was chosen to foster automaticity (Murray, 1999; Park & Ingles, 2001). In the last two months of the study, however, our original accuracy criterion was abandoned for the following reasons: (a) to target a greater diversity of attention functions as the pre-specified treatment termination date was quickly approaching when RW was still completing sustained attention tasks; (b) to placate RW's frustration with his lack of progress and the monotony of completing the same task for an extended time period; and, (c) to assure that tasks judged to have ecological validity for RW could be incorporated to foster further his motivation to complete the study.

During the latter half of the study, some modifications were introduced to simplify APT-II tasks and ensure RW's initial success when a new activity was introduced. These modifications were faded as his accuracy and/or latency improved. Specific modifications included: (a) allowing RW to write down stimuli (after they all had been presented) prior to giving his response, (b) slowing the playing speed of the pre-recorded auditory stimuli, (c) providing visual cues (e.g., on the Serial Numbers task, a cue card with the target arithmetic rule printed on it was given as a reminder), and (d) encouraging RW to repeat each stimulus aloud as it was presented and to verbalize continuously each stimulus until giving his final response. The exact number and types of strategies utilized during a given session depended on RW's initial performance of the target task that day (e.g., if he began a trial with consecutive errors, strategies were introduced until he accurately performed several consecutive trials) and the nature of APT-II task being completed (e.g., neither repeating stimuli aloud nor providing visual cues were appropriate for the time monitoring task).

For the final two treatment sessions, generalization activities were developed based on, at least in part, APT-II recommendations (Sohlberg et al., 2001). These tasks consisted of listening to and recalling directions, phone calling for driving directions, and tracking

Table 2  
APT-II treatment activities and data

APT-II tasks	Activity example/description	No. of sessions to criterion <sup>a</sup>	Initial session perform. range	Final session perform. range
<b>Sustained attention</b>				
<b>Attention tapes</b>				
Level I	From a word list, identify items that are round	4	79–94%	88–98%
Level II	From a word list, identify words related to the previously heard word	6	76–88%	88–95%
Level III	From a word list, identify words with more than one spelling	6	74–89%	83–97%
Level IV	From a word list, identify words that when spelled backwards make a word	11	75–80%	83–97%
Paragraph Listening	Select best ending (choice of 3) for paragraphs that vary from 2–6 sentences in length	3	80–100%	90–100%
<b>Alphabetized sentences</b>				
Four word level	Give back words from the sentence stimuli in alphabetical order	16 <sup>b</sup>	39–62% 34–38 s <sup>c</sup>	76–88% 22–27 s
<b>Number sequence ascending</b>				
Four number level	Give back number sequence in ascending order	5	70–80% 10–12 s <sup>c</sup>	90–100% 6–10 s
Mental math	Give back series of four numbers by adding three to each number	1	90–100% 12–15 s <sup>c</sup>	
<b>Alternating attention</b>				
Serial numbers	Continually give back a number by alternating between two arithmetic rules (i.e., addition and subtraction) for a set period of time	1 <sup>d</sup>	60–100%	

Table 2 (Continued)

APT-II tasks	Activity example/description	No. of sessions to criterion <sup>a</sup>	Initial session perform. range	Final session perform. range
Selective attention				
Mental math with noise distractor	In the presence of audiotaped or live noise, give back series of 4 numbers by adding or subtracting a given amount to each number	1 <sup>d</sup>	0–80% 9–34 s <sup>c</sup>	
Mental math with movement distractor	Same mental math activity as above but in the presence of live noise and movement (e.g., clinician shuffling papers in RW's field of view)	1 <sup>d</sup>	0–60% 21–39 s <sup>c</sup>	
Divided attention				
Time monitoring intervals on a clock	Complete a math worksheet while monitoring time	1 <sup>d</sup>	Math: 60–90% time intervals: 90–100%	

<sup>a</sup> Accuracy criterion = 90% correct over three consecutive trials.

<sup>b</sup> Accuracy criterion never reached. Instead, a new APT-II task was targeted when RW became frustrated with the sentence task due to the number of sessions spent on it and his inability to achieve further progress.

<sup>c</sup> Average response latency per item across stimulus lists.

<sup>d</sup> The original accuracy criterion was abandoned to: (a) maintain RW's interest and motivation, and (b) target a greater variety of APT-II and generalization tasks before terminating treatment.

football scores and other statistics while watching a video. For each task, RW answered 4–5 open-ended, content-based questions, and retold the information he had acquired. At the beginning of these sessions, RW was reminded about previously used compensatory strategies.

## 4. Results

### 4.1. APT-II treatment tasks

Overall, RW's accuracy, latency, or both on all trained APT-II tasks improved across trials and/or sessions (see Table 2). Although he quickly advanced through the initial sustained attention activities, he showed much slower progress on subsequent tasks that clearly stressed auditory-verbal, working memory as well as sustained attention. For example, RW failed to meet criterion (i.e., 90% accuracy over three consecutive trials) on the alphabetized sentence tasks despite eight weeks of practice and implementation of several strategies designed to reduce working memory demands (e.g., writing down stimuli after they were presented). In contrast, he achieved criterion on the next two sustained attention tasks fairly quickly, even though according to the APT-II's hierarchical organization (Sohlberg et al., 2001), these tasks should be more complex and thus, require more treatment to master.

During the last 2 months of treatment, only one session (but several trials) was typically devoted to each APT-II task because the end of the treatment phase was rapidly approaching and the original accuracy criterion had been abandoned. RW demonstrated greater difficulty on these more complex, alternating, selective, and divided attention tasks: His initial trial accuracies were lower, he required more cues to apply compensatory strategies, and more task modifications were needed to assist his performance on initial trials compared to previous APT-II activities (see Table 2). Within each session, however, RW improved across trials, even when task modifications and cues were faded. For example, across the six trials of mental math with distracter noise, RW's accuracy improved from 0 to 80% while his average trial RT decreased from 34 to 9 s.

Because of the design of the generalization tasks and time constraints, only two trials of each task were completed per session (see Table 3). During these tasks, RW independently utilized several previously reviewed strategies (e.g., taking notes), and during second trials,

Table 3  
Generalization treatment activities and data

Generalization task	No. of trials	Initial trial perform. range	Final trial perform. range
Retell directions to a local apartment complex	2	3/5 Correct unable to retell	4/5 Correct able to retell
Retell directions to get to a waterfall in a park in California	2	3/5 Correct unable to retell	5/5 Correct able to retell
Make phone call to get directions from Bloomington to Philadelphia	2	4/5 Correct able to retell	5/5 Correct able to retell
Provide score and other numerical details while watching a videotaped football game	2	1/4	2/4 Correct

his performance consistently improved. He also reported that he perceived these activities to be more helpful than APT-II tasks because they helped him determine when and how attention and memory strategies could be utilized in his daily activities and environments.

#### 4.2. Probe tasks

During treatment, RW displayed a trend towards improved listening accuracy and RT on the paragraph probe (see Fig. 1). These accuracy improvements, however, appeared related, at least in part, to exposure effects because his accuracy performance varied little on the paragraph probe set presented only prior to and following treatment. In contrast, RW achieved faster RTs on this probe set following treatment versus during baseline. This finding suggested that improved speed on the other paragraph probes was unlikely due to exposure effects alone.

To help objectify our visual inspection of these data, Shewart-chart trend lines (Robey, Schultz, Crawford, & Sinner, 1999) were calculated (see Fig. 2). The upper Shewart line

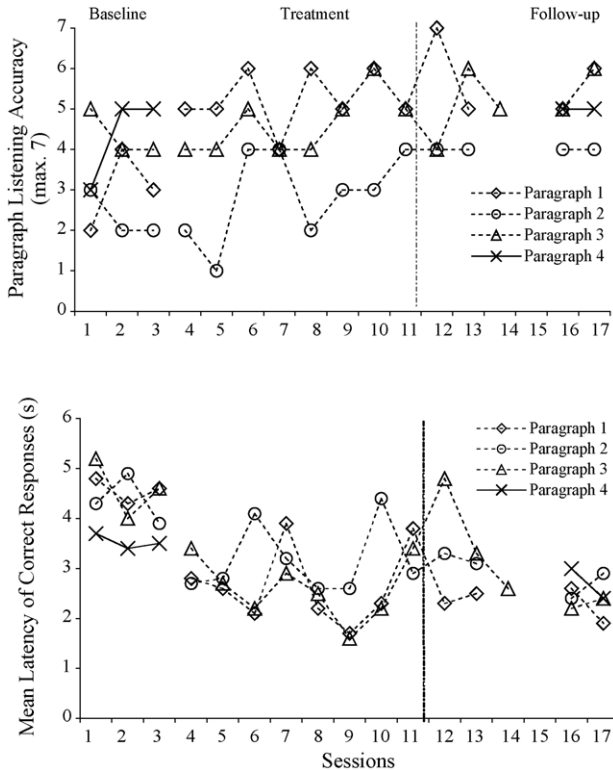


Fig. 1. RW's performance on the paragraph listening probe task across baseline, treatment, and follow-up phases. The upper graph represents accuracy data and the lower graph represents response latency data. In both graphs, paragraph 4 was the stimulus set that was completed only during baseline and follow-up phases to examine for exposure effects. The dashed vertical line in both graphs indicates the point at which the original accuracy criterion for APT-II treatment tasks was abandoned.



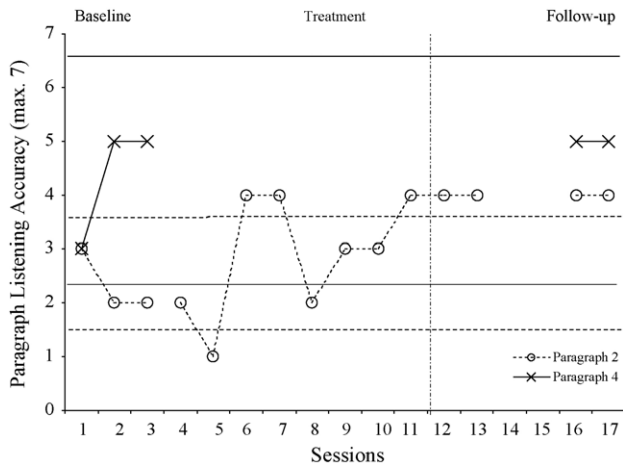


Fig. 2. Examples of Shewart-chart trend lines (Robey et al., 1999) that were used to examine for treatment effects in probe task data. The solid horizontal lines represent the upper and lower Shewart lines for paragraph 4 data, and the dashed horizontal lines represent the upper and lower Shewart lines for paragraph 2 data. According to the guidelines of Robey et al. (1999), a treatment effect is present for paragraph 2 data, whereas there is no substantive change in RW's performance in response to paragraph 4. The dashed vertical line indicates the point at which the original accuracy criterion for APT-II treatment tasks was abandoned.

represents two S.D. above the mean of the baseline data for a given stimulus set, and the lower line represents two S.D. below that baseline mean. According to Robey et al. (1999), substantive change has occurred if at least two successive data points within the treatment phase fall outside of these horizontal lines. Analysis of the paragraph accuracy data indicated that RW's performance of only probe paragraphs 1 and 2 improved. Review of Shewart-chart lines for paragraph RT data indicated that compared to his baseline performance, RW responded considerably more quickly over time during the treatment phase, and continued to do so during follow-up sessions.

On the control, RAN probe, RW showed an abrupt increase in naming rate at treatment onset, despite a relatively stable baseline (see Fig. 3). Despite some fluctuation on subsequent treatment phase probes, his naming rates during follow-up approximated those obtained during the first treatment phase probe. Shewart-chart lines indicated that RW named correctly considerably more pictures during treatment and follow-up versus baseline. Because substantive positive change also was observed in the RAN probe set given only prior to and following treatment, RAN improvements are unlikely due to only exposure or practice effects.

#### 4.3. Post-treatment tests

Table 1 displays RW's performance of the test battery administered one to two weeks following treatment termination. Minimal change was observed in his basic language (i.e., no ADP post-treatment scores fell outside the confidence range for their respective pre-treatment scores) or high-level language abilities (i.e., nominal changes on the TLC-E). Furthermore, there was little change in how RW and his spouse rated the adequacy of his

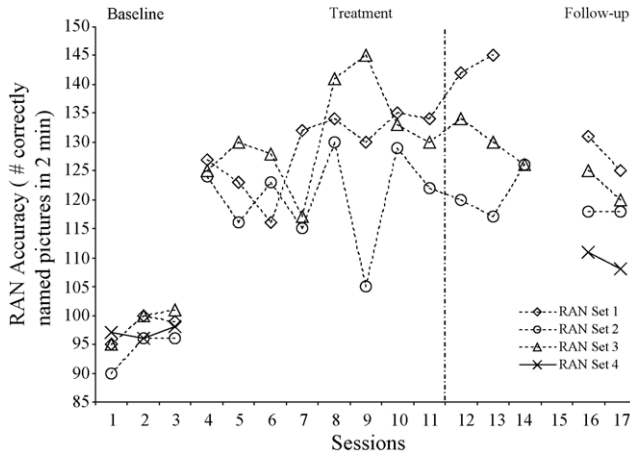


Fig. 3. RW's performance on the rapid naming (RAN) probe task across baseline, treatment, and follow-up phases of the experiment. RAN set 4 was the stimulus set that was completed only during baseline and follow-up phases to examine for exposure effects. The dashed vertical line indicates the point at which the original accuracy criterion for APT-II treatment tasks was abandoned.

communication abilities following treatment (i.e., their pre- and post-treatment CETI ratings differed by less than the standard error of 5.87 reported by Lomas et al., 1989).

Moderate improvements on some attention and memory measures were noted (see Table 1). For example, RW made fewer word recall and true/false errors on the Working Memory Task; these changes were considered substantive because they far exceeded the standard error of measurement (SEM) reported by Lehman and Tompkins (1998) for healthy adults (SEM = 0.6) or adults with right hemisphere brain damage (SEM = 0.9) (SEM data for adults with aphasia have not yet been reported). Despite this improvement, his working memory scores still fell outside the range for healthy adults (Tompkins et al., 1994). Although RW achieved some higher WMS-R raw scores, particularly on subtests most similar to APT-II tasks used in treatment (e.g., forwards and backwards digit span), these gains did not appear significant when reliable change indices (RCI; Jacobson & Truax, 1991; Sawrie, Chelune, Naugle & Luders, 1996) were calculated.

RW achieved higher scaled scores on seven TEA subtests. Post-treatment gains on only map search (second minute) (i.e., a sustained and selective attention task) and telephone search while counting (i.e., a divided attention task), however, exceeded RCI values (Jacobson & Truax, 1991; Sawrie et al., 1996) and thus were considered substantial. Minimal changes were noted when comparing the pre- and post-treatment ratings of RW and his spouse on the APT attention questionnaire.

## 5. Discussion

In the current study, APT-II (Sohlberg et al., 2001), a structured treatment protocol designed to remediate attention deficits associated with mild TBI, was given to RW, a

patient with chronic, conduction aphasia and concomitant attention and working memory impairments. Purposes of the study were to explore not only whether RW would display improvement on trained attention tasks and related tests of attention, but also whether these improvements would facilitate positive change in his auditory comprehension and other cognitive abilities, and in his and his spouse's perceptions of his daily attention and communication abilities.

Within APT-II treatment sessions, RW demonstrated gradual improvements in response accuracy, latency, or both. These findings indicated that RW's language impairments did not preclude his completion of APT-II tasks. Furthermore, he was able to acquire the specific attention skills that APT-II targets with similar success as that reported for TBI patients (Palmease & Raskin, 2000) and as that observed when different structured attention training programs have been given to stroke patients (Sturm et al., 1991, 1997).

It should be noted, however, that APT-II's hierarchical organization did not completely correspond with the degree of difficulty RW displayed across activity levels and stimuli lists. For example, even following 16 sessions, RW never met our a priori accuracy criterion on the "simplest" sustained attention task, alphabetized sentences. In contrast, on mental math, which according to the APT-II manual should be the most difficult sustained attention activity, he achieved criterion within one session. An important clinical implication of this finding is that when using APT-II with patients who have concomitant language symptoms, particular attention to the linguistic demands of tasks must be considered when planning the progression of task difficulty levels. For instance, alphabetized sentences will typically be the most difficult sustained attention activity for many aphasic patients because it requires phoneme-to-grapheme conversion (Rapp & Gotsch, 2001) whereas other APT-II sustained attention tasks do not. Clearly, further research is needed to establish the reliability and validity of the APT-II task hierarchy for not only patients with co-existing language impairments, but also those whose symptom profiles are more consistent with the patient population for whom APT-II was developed.

Test battery data also suggested that some of RW's specific attention skills had improved. That is, following treatment, RW tended to show greatest improvement, albeit modest, on tests similar to either trained APT-II activities or the probe tasks to which he was repeatedly exposed. More specifically, RW achieved substantially improved post-treatment scores on TEA map search – second minute, TEA telephone search while counting, and the working memory task. Like RW's treatment protocol, these tests require sustained, selective, and divided attention and/or working memory, and emphasize information processing speed. Relatedly, recurring exposure to the RAN probe task (which required visual sustained attention/scanning and fast information processing) may account for, at least in part, RW's improvement on visual attention TEA subtests, even though auditory attention was the primary focus of his APT-II treatment.

A focus of this study was to determine whether APT-II treatment effected positive changes in RW's auditory comprehension as well as other cognitive abilities. Probe findings indicated some improvement in his listening abilities: Compared to baseline, he achieved substantially faster latencies on the paragraph listening probe task as treatment

progressed, and maintained this improvement during follow-up probe sessions. Other auditory comprehension measures (i.e., ADP and TLC-E subtests, paragraph listening probe response accuracy), however, were associated with no apparent treatment-related changes. These findings are not as encouraging as those of Helm-Estabrooks et al. (2000). These researchers' two aphasic patients displayed small (i.e., 6–7 percentile point increases on the auditory comprehension subtests of the *Boston Diagnostic Aphasia Examination*) but “functionally meaningful gains in auditory comprehension” (p. 472) following structured attention training. As previously mentioned, however, Helm-Estabrooks and colleagues' results should be interpreted cautiously because of design limitations. Likewise, these researchers did not specify whether their patients' auditory comprehension score improvements exceeded expected practice effects or how their “functionally meaningful gains” were objectively quantified. Additionally, disparity between our results and those of Helm-Estabrooks et al., 2000 may be related to subject (i.e., RW's auditory comprehension appeared less impaired than that of Helm-Estabrooks et al.'s patients) or procedural differences (e.g., auditory–verbal versus visual–nonverbal treatment activities, treatment intensity). Accordingly, further research is needed to establish whether auditory comprehension or other linguistic deficits associated with aphasia might benefit from attention training, and what patient or treatment variables might influence the magnitude of treatment effects.

One somewhat unexpected finding was that RW displayed improvements on the RAN probe task that could not be attributed to exposure effects alone. In view of multiple resource models of attention (e.g., McLeod, 1977; Wickens, 1989), we originally hypothesized that RW's RAN performance would demonstrate little change because this task primarily stresses visual attention whereas APT-II stresses auditory attention. In hindsight, however, RAN completion does involve some of the same skills targeted in treatment. For example, many APT-II tasks required RW to give quick and continual verbal responses, albeit in response to auditory stimuli (e.g., alphabetized sentences, mental math). Therefore, RAN improvements might be a product of practicing rapid verbal responses during treatment activities. Another possibility is that attention treatment improved RW's information processing speed (regardless of input modality), which in turn enhanced his performance of RAN and other speeded tasks (e.g., response latency on the paragraph listening probe, TEA map search, TEA telephone search while counting).

RW displayed nominal change on attention and memory tests that were less related to treatment or probe tasks (e.g., WMS-R visual reproduction). These findings are consistent with those of past investigations regarding the effects of structured attention training programs, including APT and APT-II, on the cognitive abilities of patients with TBI (Gray, Robertson, Pentland, & Anderson, 1992; Niemann, Ruff, & Baser, 1990; Palmese & Raskin, 2000; Park et al., 1999; Sohlberg et al., 2000), aphasia (Helm-Estabrooks et al., 2000; Sturm et al., 1991, 1997), or right hemisphere brain damage (Sturm et al., 1991, 1997). This pattern of treatment effects has led several researchers to propose that structured attention retraining is most likely to evoke change in specific skills rather than enhance cognitive functions per se (Cicerone et al., 2000; Park & Ingles, 2001; Park et al., 1999). Review of RW's performance of the test battery and probe tasks indicates that his outcomes are consistent with this proposal as well.

Despite improvements on trained APT-II activities and modest increases on certain probe tasks and formal tests, little change was observed on questionnaires designed to quantify and qualify changes in the perceptions of RW and his wife. Our review of the attention retraining literature indicated that hardly any studies incorporated measures to examine patients' and caregivers' views of treatment outcomes, and thus there were limited results with which to compare our findings. In the few investigations that did utilize patient or caregiver questionnaires, findings were similar to ours: Structured attention treatments were not associated with significant positive change in the patients' or caregivers' perceptions of the patients' cognitive impairments or daily functioning (Novack, Caldwell, Duke, Bergquist, & Gage, 1996; Ponsford & Kinsella, 1988; Thomson, 1995).

Sohlberg et al. (2000) also found no significant effects of APT treatment on the questionnaire responses of their TBI patients. During a structured interview, however, their patients who showed most improvement on a standardized test of attention reported the greatest number of positive changes in attention and memory following APT. Sohlberg et al. (2000) conjectured that the concrete thinking of TBI patients may lead them to report changes only when they are asked about tasks, events, and abilities that are specific to their personal lives (versus the generic and broad tasks, events, and abilities about which questionnaires typically ask). Whereas this proposition may explain, at least in part, the lack of positive questionnaire findings for TBI patients, it does not account for why caregivers' questionnaire responses in the current and previous studies (e.g., Ponsford & Kinsella, 1988) suggest unimpressive treatment outcomes. An alternate but associated explanation may relate to the psychometric properties of the questionnaires being utilized. That is, in many cases, the reliability and validity of the questionnaires have not yet been reported. For example, with respect to the current study, although the psychometric properties of the CETI have been published (Lomas et al., 1989), those of the APT-II Attention Questionnaire have not. Therefore, psychometric limitations may be confounding patient and caregiver questionnaire responses. Finally, it remains possible that retraining attention via structured tasks is not the most efficient means to evoke changes in daily attention functioning that are meaningful or observable to patients and their caregivers. This explanation is supported by the more encouraging functional outcomes reported following goal-based and strategy-training interventions (which incorporate tasks similar to our generalization activities) (Cicerone, 2002; Manly, Ward & Robertson, 2002; Park & Ingles, 2001; Wilson, 1996; Wilson & Robertson, 1992). Accordingly, these treatments may represent more effective or efficient approaches to attention rehabilitation.

Collectively, the present and previous findings (e.g., Park et al., 1999; Sturm et al., 1991, 1997) regarding the effects of APT, APT-II, and other structured attention training programs suggest that for patient populations with aphasia or TBI improvements may be limited to specific attention skills; positive changes in broader cognitive functions, untrained cognitive skills, and patients' and caregivers' perceptions of their impairments are less likely. Following over 50 h of attention training, RW achieved only modest gains on standardized tests and probe tasks that were closely related to APT-II activities, and neither RW nor his spouse reported noticeable positive changes in his daily communication or attention abilities. Whereas our initial findings raise doubt that structured attention programs such as APT-II represent a viable or efficient approach to treating concomitant

attention problems in patients with aphasia, clearly further research is needed not only to determine the reliability and validity of our results, but also to inform discrimination of attention treatment approaches (e.g., retraining versus skills-training versus strategy teaching versus combined approach) for patients with aphasia.

### Acknowledgements

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### Appendix A. Example of the paragraph listening probe task

Although stage plays have been set to music since the era of the ancient Greeks when the dramas of Sophocles and Aeschylus were accompanied by lyres and flutes, the usually accepted date for the beginning of opera, as we know it is 1600. As part of the celebration of the marriage of King Henry IV of France to the Italian aristocrat Maria de Medici, the Florentine composer Jacopo Peri produced his famous *Euridice*, generally considered to be the first opera. Following his example, a group of Italian musicians, poets, and noblemen called the *Camerata* began to revive the style of musical story that had been used in Greek tragedy. The *Camerata* took most of the plots for their operas from Greek and Roman history and mythology, writing librettos or dramas for music. They called their composition opera in musica or musical works. It is from this phrase that the word “opera” is borrowed.

For several years, the center of operas was Florence, but gradually, during the baroque period, it spread throughout Italy. By the late 1600s, operas were being written and performed in Europe, especially in England, France, and Germany. But, for many years, the Italian opera was considered the ideal, and many non-Italian composers continued to use Italian librettos. The European form de-emphasized the dramatic aspect. New orchestral effects and even ballet were introduced under the guise of opera. Composers gave in to the demands of singers, writing many operas that were nothing more than a succession of brilliant tricks for the voice. Complicated arias, recitatives and duets evolved. The aria, which is a long solo, may be compared to a song in which the characters express their thoughts and feelings. The recitative, which is also a solo, is a recitation set to music whose purpose is to continue the story line. The duet is a musical piece written for two voices, which may serve the function of either an aria or a recitative.

1. This passage is a summary of:
  - (a) opera in Italy
  - (b) the *Camerata*
  - (c) **the development of opera**
  - (d) *Euridice*
2. According to this passage, when did modern opera begin?
  - (a) In the time of ancient Greeks
  - (b) In the fifteenth century

- (c) At the beginning of the sixteenth century  
(d) **At the beginning of the seventeenth century**
3. According to the author, what did Jacopo Peri write?  
(a) Greek tragedy  
(b) **The first opera**  
(c) The opera Maria de Medici  
(d) The opera The Camerata
4. The author suggests that Euridice was produced:  
(a) in France  
(b) originally by Sophocles and Aeschylus  
(c) without much success  
(d) **for the wedding of King Henry IV**
5. What was the Camerata?  
(a) A group of Greek musicians  
(b) **Musicians who developed a new musical drama based up Greek drama**  
(c) A style of music not known in Italy  
(d) The name given to the court of King Henry IV
6. From what did the term “opera” derive?  
(a) Greek and Roman history and mythology  
(b) Non-Italian composers  
(c) **The Italian phrase that means “musical works”**  
(d) The ideas of composer Jacopi Peri
7. Which of the following is an example of a solo?  
(a) **A recitative**  
(b) A duet  
(c) An opera  
(d) A lyre

*Note:* Correct answers are in bold font. The passage was adapted from materials published by [Educational Testing Service \(1998\)](#).

## **Appendix B. Continuing education self study questions**

1. Previous research regarding attention abilities in adults with aphasia has indicated that:
- (a) adults with aphasia only demonstrate attention deficits when tasks have heavy linguistic demands  
(b) adults with aphasia only demonstrate attention deficits when tasks involve auditory stimuli  
(c) adults with aphasia only demonstrate attention deficits in the acute stages of recovery  
(d) adults with aphasia demonstrate deficits of primarily sustained attention  
(e) adults with aphasia may demonstrate deficits in one, a combination, or all aspects of attention

2. An attentional or processing model of aphasia proposes that:
  - (a) the linguistic impairments of adults with aphasia compromise their attention abilities
  - (b) aphasic symptoms are a product of decreased processing speed
  - (c) aphasic symptoms are a product of or exacerbated by attention impairments
  - (d) aphasic symptoms and attention impairments are a product of decreased working memory capacity
  - (e) only aphasic comprehension impairments are a product of or exacerbated by attention impairments
3. The attention treatment used in the current study consisted of:
  - (a) Helm-Estabrooks and colleagues' (2000) Attention Training Program
  - (b) Sohlberg and Mateer's (1986) Attention Process Training
  - (c) Sohlberg and colleagues' (2001) Attention Process Training-II
  - (d) Attention Training Program and generalization activities
  - (e) Attention Process Training-II and generalization activities
4. In the current study, treatment effects were documented by:
  - (a) comparing pre- and post-treatment test battery outcomes and examining performance on probe tasks
  - (b) comparing pre- and post-treatment test battery outcomes
  - (c) examining performance on probe tasks
  - (d) evaluating performance on the final attention treatment activity
  - (e) eliciting patient and caregiver feedback regarding their opinions of treatment activities
5. The findings of the current study indicated that:
  - (a) structured attention training produced significant improvements in not only our aphasic patient's attention abilities, but also his auditory comprehension and other cognitive skills
  - (b) structured attention training produced greatest improvements in those cognitive skills most closely related to treatment and probe tasks
  - (c) our patient and his caregiver reported noticeable improvements in his daily attention and communication abilities following treatment
  - (d) attention deficits in adults with aphasia cannot be remediated
  - (e) structured attention training for adults with aphasia should utilize tasks with linguistic versus nonlinguistic content

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