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Task Switching and Attention Deficit Hyperactivity Disorder

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The main goal of the present set of studies was to examine the efficiency of executive control processes and, more specifically, the control processes involved in task set inhibition and preparation to perform a new task in attention deficit hyperactivity disorder (ADHD) and non-ADHD children. This was accomplished by having ADHD children, both on and off medication, and non-ADHD children perform the task-switching paradigm, which involves the performance of two simple tasks. In nonswitch trials, an individual task is performed repeatedly for a number of trials. In switch trials, subjects must rapidly and accurately switch from one task to the other, either in a predictable or unpredictable sequence. Switch costs are calculated by subtracting performance on the nonswitch trials from performance on the switch trials. These costs are assumed to reflect the executive control processes required for the coordination of multiple tasks. ADHD children showed substantially larger switch costs than non-ADHD children. However, when on medication, the ADHD children's switch performance was equivalent to control children. In addition, medication was observed to improve the ADHD children's ability to inhibit inappropriate responses. These data are discussed in terms of models of ADHD and cognition.

KEY WORDS: Executive control; attention; inhibition; ADHD; child development; task switching.

The main goal of the present study was to examine differences in performance in the task switching paradigm among attention deficit hyperactivity disorder (ADHD) children on and off medication and age and IQ matched controls. This paradigm was employed in an effort to decompose and examine, in a fine-grained manner, a number of aspects of information processing that have been hypothesized to be less efficient in ADHD children than in non-ADHD children (Barkley, 1989, 1997; Douglas, 1983; Schachar *et al.*, 1993; Seidman *et al.*, 1995). More specifically, the task-switching paradigm has enabled us to examine executive control processes (Norman & Shallice, 1986; Meyer *et al.*, 1997; Shallice, 1994) required to prepare to perform a task as well as those control processes involved in the inhibition of previously activated processing algorithms.

Two different classes of models have been proposed to account for the behavioral deficits observed in ADHD children. One class of models has argued that the behavioral deficits are the result of deficient inhibitory processing in ADHD (Barkley, 1997; Pennington & Ozonoff, 1996; Schachar *et al.*, 1993, 1995; Quay, 1988, 1996). The most comprehensive of such theories has been proposed by Barkley (1997). This model suggests that faulty inhibition is the core deficit in ADHD and this deficit is responsible for secondary deficits observed in other neuropsychological functions, including working memory, self-regulation of affect and motivation, internalization of speech, and behavioral analysis and synthesis. The alternative class of models suggests that behavioral deficits observed in ADHD are the result of either deficient resource allocation policies (Sergeant, 1995a,b) or reduced arousal (Zentall, 1985). We contrast these two classes of models in the present study by examining the performance of ADHD children (on and off medication) with control children in situations that enable the dissociation of changes in resources and arousal with changes in the need for inhibitory processes.

Another goal of the present study is to more finely delineate the nature of the inhibitory deficit associated with ADHD. It has become increasingly clear that inhibition is not a unitary construct, but instead varies along a

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number of dimensions (Neill & Valdes, 1996), and that different varieties of inhibition can be dissociated in certain populations, such as older adults (Kramer *et al.*, 1994). In the present study, we employ a relatively well-studied paradigm from Cognitive Psychology called the *task-switching paradigm* to enable us to decompose the nature of inhibitory and executive control deficits observed in ADHD and, in addition, to examine the efficacy of pharmacologic intervention as a means to reduce inhibitory deficits in ADHD children.

EXECUTIVE CONTROL AND INHIBITION IN THE TASK-SWITCHING PARADIGM

The task-switching paradigm involves the performance of two simple tasks, such as deciding whether a letter is a vowel or a consonant or deciding whether a number is odd or even. In one condition (i.e., the nonswitch baseline or repetition condition), the same task is repeated a number of times. In the second condition (i.e., the switch or alternation condition), subjects switch from one task to the other. The time required to complete the executive control processes necessary to switch from one task to another, such as the selection from long-term memory and configuration in working memory of the appropriate processing algorithms and the inhibition of previously used processing algorithms, is inferred from the increased response time (RT) observed when a task switch occurs, compared to the RT for the same task performed separately or in a run of trials of the same task (i.e., switch cost RT = switch trial RT − nonswitch trial RT).

Several interesting results been observed in the task switching paradigm. First, several investigators have obtained data which suggest that executive control processes and task component processes (i.e., processes used to perform the separate tasks such as encoding, stimulus evaluation, response selection, and response execution) are functionally independent. For example, Gopher (1996) reported that instructions concerning the likelihood and nature of a switch influenced switching time but not component task time (i.e., nonswitch time). Rogers and Monsell (1995) found that the time allotted to prepare for a task switch had a substantially larger influence on switch time than it did on component task time, whereas the presence of a warning cue influenced component task time but not switching time (see also Kramer *et al.*, 1999; Lauber *et al.*, 1996; Rubinstein *et al.*, in press). In summary, the results obtained in a number of studies suggest that the processes which support switching performance are distinct, at least in part, from those processes that support performance in the separate tasks.

Researchers have also argued that multiple executive control processes can be distinguished in the task-switching paradigm. Rogers and Monsell (1995) had subjects perform a sequence of trials in which they alternated between sets of two trials in which they decided whether a letter was a vowel or a consonant, and then two trials in which they decided whether a digit was odd or even. Within this paradigm, Rogers and Monsell manipulated the response stimulus interval (RSI) between tasks from 150 and 1200 ms, and found substantial decreases in switch costs as the RSIs increased from 150 to 600 ms, but relatively stable switch costs between RSIs of 600 and 1200 ms. On the basis of these results, the authors concluded that two different executive control processes could be distinguished in the task-switching paradigm. They proposed that the decrease in switch costs observed when the RSI was increased from 150 to 600 ms were compatible with an endogenous, stagelike process of task reconfiguration that can be carried out in anticipation of the stimulus. This stagelike process likely requires the loading of processing algorithms required for the new task into working memory and the inhibition of the processing algorithms that are no longer appropriate. However, such an endogenous preparatory process cannot be the whole story because a substantial and stable switch cost remained as RSIs were increased from 600 to 1200 ms. To account for this effect, the authors argued that a component of the task reconfiguration process cannot be executed in advance of the stimulus, but instead is triggered only exogenously by the appearance of a stimulus associated with the task to be performed (see also Merian, 1996; Rubinstein *et al.*, in press).

Finally, a number of results suggest that executive control processes which are utilized in the task-switching paradigm can benefit from practice. For example, Jersild (1927) reported that task-switching time was reduced relative to component task time with practice for a large number of different task combinations. Rogers and Monsell (1995) also observed reduced switch costs with practice in their predictable task-switching paradigm (see also Gopher, 1996; Kramer *et al.*, 1999).

TASK SWITCHING AND THE WISCONSIN CARD SORTING TASKS: SIMILARITIES AND DIFFERENCES

The task-switching paradigm bears a resemblance to another task, the Wisconsin Card Sorting Test (WCST) paradigm (Anderson *et al.*, 1991; Berg, 1948; Heaton, 1981), which has been used to examine the influence of ADHD on executive control. In the WCST paradigm

subjects are required to sort cards into different piles on the basis of the number, shape and color of geometric objects that are printed on the cards. The subject is required to discover the sorting rule on the basis of feedback provided by the tester. Following ten correct sorts, the sorting rule is changed without warning and the subject must again discover the new sorting rule on the basis of tester feedback. Performance on the WCST, particularly measures of perseverative errors, has been found to be associated with frontal lobe lesions in human patients (Drewe, 1974; Heaton, 1981; Milner, 1963) and with activation of the dorsolateral prefrontal cortex (Berman *et al.*, 1995).

Given the hypothesis of decreased frontal lobe efficiency in ADHD children (Lou *et al.*, 1989; Sieg *et al.*, 1995), particularly with regard to the inhibition of inappropriate behavior (i.e., the old response once the rule has changed in the WCST task), it might be expected that these children would have difficulty performing the WCST task. Indeed, decreased performance has been found for ADHD children as compared to control subjects in 8 out of 13 studies reviewed by Barkley *et al.* (1992). Although a number of methodological problems could be responsible, in part, for these mixed results there are also a number of other possible reasons. For example, the WCST is a complex task that requires problem solving and efficient working memory to discover the new rule after a change in addition to the ability to inhibit inappropriate responses. In addition, given that the WCST task is untimed, the failure to consistently observe higher error rates among ADHD children might be the result of a speed/accuracy tradeoff (i.e., the ADHD children are increasing accuracy by taking more time to perform the task).

Given that the rules for task performance are predefined in the task-switching paradigm (Rogers & Monsell, 1995), performance in this paradigm does not depend on subjects' abilities to problem solve, as in the WCST task. The task-switching paradigm also includes the measurement of both RT and accuracy, so the possibility of speed/accuracy tradeoffs between control and ADHD groups can be evaluated. Finally, the task-switching paradigm includes a baseline (i.e., the nonswitch trials) against which switch performance can be compared. In summary, the task-switching paradigm offers a number of advantages if one is interested in ADHD effects on preparatory processes and inhibition.

Experiment 1

The present study was conducted to examine two primary issues. First, we were interested in determining whether performance differences between ADHD and control children and also between medicated and unmedicated ADHD children would be general or specific. That is, we wanted to determine whether differences between groups would be specific to aspects of the task-switching paradigm that are associated with executive control processes, such as the inhibition of inappropriate task sets and responses and preparatory processes associated with switching between two different tasks. More specifically, we were interested in testing the hypothesis that unmedicated ADHD children would show substantially larger switch costs (i.e., switch cost RT = RT on switch trials − RT on nonswitch trials) than control children, suggesting deficient executive control processes and in particular the control processes necessary for the disengagement from one task and preparation for a subsequent task. We were also interested in determining whether medication would assist the ADHD children in more effectively employing executive control processes in the task-switching paradigm. That is, we wished to determine whether switch costs of ADHD children on medication would be equivalent to those observed for control children. Switch-specific performance differences would suggest processing differences attributable to executive control processes concerned with task preparation and inhibition, consistent with Barkley's (1997) executive function model of ADHD (see also Pennington & Ozonoff, 1996; Schachar *et al.*, 1993, 1995; Quay, 1988, 1996), whereas similar patterns of performance differences on switch and nonswitch trials would suggest more general information processing differences between ADHD and control children (and between ADHD children on and off medication).

Within the context of the experimental design employed in the present study, we predicted significant two-way interactions between subject group and trial type (switch vs nonswitch trials) for the medicated vs the unmedicated ADHD children and for the control vs unmedicated ADHD children, but not for the medicated ADHD vs the control children. That is, the executive control conception of ADHD predicts that unmedicated ADHD children will show a greater RT cost when required to switch between tasks than the same children on medication or control children. It is also conceivable that such switch costs will be further exacerbated when the response requirements conflict between the two tasks (i.e., on the incompatible vs on the response compatible trials in our paradigm).

The paradigm also enabled us to contrast inhibitory models of ADHD with resource allocation deficiency (Sergeant, 1995a,b) and arousal (Zentall, 1985) based conceptions of ADHD by comparing performance on nonswitch trials in switch and single-task blocks. It seems reasonable to assume that subjects will be more aroused

in trial blocks in which task switches can occur (and also be more willing to allocate additional resources to maintain performance in these trial blocks) than in trial blocks in which it is certain that only a single task will be repeatedly performed. Therefore, the resource allocation/arousal models would predict poorer performance for ADHD than for control children for nonswitch trials in switch blocks than for these same trials in single-task blocks. However, the need for inhibitory processing is unlikely to differ between switch and single-task blocks for the nonswitch trials, and therefore inhibition-based models of ADHD would not predict a difference in performance for ADHD and control children on these trials.

Within the context of the experimental design employed in the present study, the resource allocation/arousal deficiency models predict a two-way interaction between group and block type (switch vs single-task blocks). That is, that unmedicated ADHD children would show larger costs to perform nonswitch trials in the switch than in the single-task blocks than the same children on medication and control children. However, executive control deficiency models of ADHD do not predict such an interaction.

In an effort to examine these theoretical questions, we asked the children to perform two simple tasks. On each trial, either 1 or 3 digits were presented on the computer screen. In one task, subjects were asked to indicate how many numbers were on the screen. In the other task, subjects were asked the value of the digits on the screen. Subjects performed each of these tasks separately in a block of trials (single-task blocks). In a third block of trials, subjects switched between the two tasks on every third trial (switch blocks).

Switch costs were computed in the switch-trial block by subtracting the nonswitch-trial RTs (i.e., trials on which the same task repeated) from switch-trial RTs (i.e., trials on which subjects switched from one task to the other). Performance was also contrasted between the single-task blocks and the nonswitch trials in the switch block in an effort to evaluate the performance costs associated with anticipating a switch between tasks.

Given that the two tasks both required responding with a 1 or a 3, we could also evaluate the difference in performance when both responses were compatible (i.e., when the task to be performed and the other task both required responding with a 1 or a 3) as compared to when the responses were incompatible. Incompatible responses in similar paradigms have previously been shown to be responded to more slowly and less accurately than compatible responses (Coles *et al.*, 1985; Eriksen & Eriksen, 1974; Eriksen *et al.*, 1985). Furthermore, the magnitude of the difference between compatible and incompatible responses has been reported to be larger for ADHD children than for control children in the Stroop paradigm, in which subjects are required to verbalize the color of the ink in which a response-compatible (e.g., the word *red* printed in red ink) or response-incompatible (e.g., the word *red* printed in blue ink) word is printed (Kenner *et al.*, 1993; Seidman *et al.*, 1995). Therefore, it is conceivable that ADHD children will produce slower RTs on the incompatible than on the compatible trials in our task-switching study, and that the difference in task-switch cost between the subject groups might be increased on the incompatible as compared to the compatible response trials. Such a finding would be informative with respect to the nature of inhibitory deficits observed in ADHD.

METHOD

Subjects

Sixteen 6 to 12-year-old children with ADHD (average age = 8.9 years, $SD = 1.1$) and 16 age- and IQ-matched controls (average age = 8.8 years, $SD = 1.4$) were run in this experiment. IQ was measured by the Kaufman K-Bit Brief Intelligence Test. The average K-Bit IQ composite scores were 93.6 ($SD = 11.9$) and 95.3 ($SD = 13.0$) for the ADHD and control children, respectively. All subject pairs (i.e., control/ADHD matched pairs) were within 0.7 years of age and 6 points on the K-Bit composite score. All children had normal or corrected-to-normal vision (20/40 or better), as measured by a Snellen acuity chart.

The ADHD subjects ($n = 16$) were from a clinical population of children receiving medical care from the second author (M. Cepeda) through the Mobile County, Alabama, Public School System Title I School Health Program. Because of funding regulations, any child receiving services for an educational handicap such as learning disabilities (LD) or mental retardation (MR) was not eligible for Title I services and thus no ADHD subjects for this study had a known learning disability or mental retardation. Thirty-one percent (5/16) had been screened prior to entry into the study for possible MR or LD (most often the Wechsler Intelligence Scale for Children–III and the Wechsler Individual Achievement test or Woodcock–Johnson Psychoeducational battery). None met Alabama Department of Education criteria for LD (based on a demonstrated discrepancy between ability and achievement by individual testing and actual academic classroom underachievement) or MR (deficits in both general intellectual functioning and adaptive behaviors).

The assessment included clinical interviews with parent(s) and subject, review of classroom observations made

by three school personnel (teachers or teacher/administrators), and a narrative and/or behavior log by a mainstream classroom teacher. All subjects were positive for ADHD (based on DSM-III-R criteria) using the computer-assisted version of the Diagnostic Interview Schedule for Children, Parent Version (CDISC-P), and positive for ADHD using *Diagnostic and Statistical Manual, Fourth Edition* (DSM-IV) clinical criteria. Subjects met DSM-IV criteria for either ADHD, combined type (i.e., met criteria for both the hyperactive/impulsive axis and inattentive axis), or the hyperactive/impulsive axis subtype. Eighty-one percent of the children (13/16) were of the combined type and 19% (3/16) were of the hyperactive type alone. The mean Conners' Teacher Rating Scale-28 (CTRS-28) Hyperkinesis Index off medication was 24 (range 17–30). The mean Hyperkinesis Index while using medication was 5 (range 2–10), for an average on-medication behavior improvement of 19 points. The dose of medication (methylphenidate) used for testing while the children were on medication was the individualized dose that had previously been shown to be clinically effective in the classroom (based on an improvement in the CTRS-28 Hyperkinesis Index). The average dose of methylphenidate was 15.3 mg (range 15–20 mg.). Medication was administered 30 to 90 min prior to experimental testing. With respect to demographics, the average family income was $17,580 (range $6,948 to $67,600). Fifty-six percent of the children were white (9/16) and 44% (7/16) were African-American. Sixty-two percent (10/16) of the children were male.

The control subjects ($n = 16$) were recruited from a sample of children attending the Boys and Girls Clubs of Mobile, Alabama, Inc., after-school program ($n = 8$), and children ($n = 8$) who responded to advertisements in Champaign-Urbana, Illinois. The children from Mobile, Alabama, came from low (60% were from families with incomes at or below 80% of the median income of $22,994 for the area) to moderate income families. The median income for control children's families from Champaign-Urbana was $27,500 (range $12,000–$50,000). The two sites were necessary to obtain sufficient control children matched (pairs) for age and K-Bit scores with the ADHD children. For the combined total of control children from both sites, 50% (8/16) were white and 50% were African-American. Thirty-eight percent (6/16) of the control children were male. All of the control children were screened with the CTRS-28 and had Hyperkinesis Indices below 17 (mean = 6, range 3–10). Learning disability status of the control children was not known (and most likely reflected the general population prevalence of 10–20%). None of the control children were being prescribed (or had been prescribed in the past) psychotropic medications that might be used to treat ADHD.

Children with ADHD were tested on and off a dose of methylphenidate that produced scores on the CTRS-28 below the criteria for hyperkinesis (below 17), typically 15 mg. Controls were tested twice, both times unmedicated, to rule out practice effects that might occur in children with ADHD, who also were tested twice. Eight children with ADHD were unmedicated during the first session, and eight were unmedicated during the second session.

The research protocols were approved by the respective institutional review boards of the University of Illinois and the University of South Alabama. All of the children were volunteers.

Stimuli

Stimuli were presented at fixation. The four possible stimuli were either a single digit (1 or 3) or three digits (1 1 1 or 3 3 3). In other words, either one or three numeric 1s or 3s were presented. Above each target stimulus, either the words, "What number?" or the words "How many?" appeared, depending on which task was being performed on that trial.

Apparatus

Children with ADHD and controls in Alabama were run using an IBM ThinkPad 760 laptop computer (Intel Pentium-75) with a 12.1 inch active matrix LCD screen. Responses were made using the 1 and 3 keys on an IBM numeric keypad attached to the laptop. Controls in Illinois were run on Gateway 2000 desktop computers (Intel 486-33) with 14 inch RBG monitors. Responses were made on the numeric keypad attached to a standard 101-key keyboard. Subjects sat about 60–80 cm from the monitor or laptop screen. This distance allowed easy discrimination of the stimuli.

Procedure

Children with ADHD were run at the University of South Alabama Department of Psychiatry during routine physician visits for medication management. Controls were run either at the Boy's and Girl's Club in Mobile, Alabama, or at the Beckman Institute of the University of Illinois at Urbana-Champaign. The room was dimly lit and at least one experimenter, and sometimes also a parent, sat in the room with the child, out of the child's field of view. For the control children, the K-Bit was administered and demographic information was collected during the first session. For the children with ADHD, analogous data had been collected during earlier office visits.

Three separate blocks of trials of the task-switching paradigm were administered during each experimental session. The first block included only "What number?" trials, the second included only "How many?" trials, and the third block (task-switching block) alternated between these two tasks after every second trial. For the first block, subjects were to identify the numeric value of the digits presented, and for the second block, subjects were to identify the number of digits on the screen. Half the trials contained stimuli that were response compatible (i.e., the task that was currently being performed and the other task—1 or 3 3 3) and half the trials contained response-incompatible stimuli (1 1 1 or 3).

The first two blocks contained 24 experimental trials each, and the third block contained 72 experimental trials. Trials were subject-paced, in which a response on one trial initiated the next trial. A variable response–stimulus interval (RSI) of 300–600 ms was used for all blocks. In all blocks, the task cue appeared at the same time the imperative stimulus appeared. When errors were made, a 100-ms, 1000-Hz tone sounded. Total time to complete the experiment was about 15–20 min. Sufficient practice to learn the task, typically 10–20 trials, was provided before each block. Breaks were allowed between blocks, when needed. Figure 1 illustrates the time course of an experimental trial.

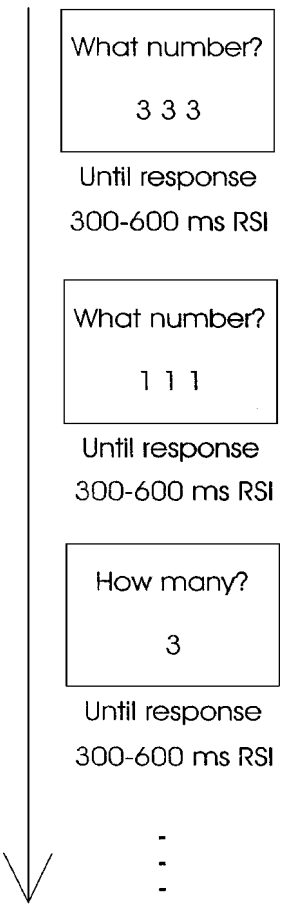

Fig. 1. An illustration of the trial sequence in the switch block of Experiment 1. A task change occurred after every second trial. Nonswitch blocks followed the same time course, but the task did not alternate every second trial. RSI refers to response–stimulus interval.

RESULTS AND DISCUSSION

The data, reaction times (RT) and errors, obtained in the task switching paradigm were submitted to a series of analyses of variance (ANOVAs).[3] Mean RTs included only correct trial responses. False alarms (responses faster than 200 ms) were rare, with fewer than 1% false alarms for all experimental groups and conditions. Therefore, trials on which a false alarm occurred were not analyzed further.

Comparison of Switch and Nonswitch Trials in Switch Blocks

Table I presents the mean of the median RTs obtained from the ADHD children, on and off medication, and the control children. The comparable error rate data are also presented in Table I. These data were analyzed in a number of ANOVAs that all included the within-subjects factors of trial type (nonswitch and switch trials within the trial block in which tasks switched after every two trials) and response compatibility (compatible or incompatible responses in the currently relevant and irrelevant task). In our first set of ANOVAs we compared ADHD children on and off medication. For RT, significant main effects were obtained for compatibility ($F(1, 15) = 4.9$, $p < .05$) and trial type ($F(1, 15) = 23.8$, $p < .01$). RTs were faster when the responses for the two tasks were compatible than when they were incompatible. RTs were also faster for nonswitch trials (in trial blocks in which task switches could occur) than they were for trials on which subjects switched from one task to the other. Error rates were higher for the incompatible than for the compatible response conditions

[3]Preliminary analyses indicated statistically equivalent performance for the control children from Alabama and Illinois in the task-switching paradigm. Therefore, these two groups of control children are combined in all comparisons with the ADHD children.

Table I. Reaction Times (RTs) Presented in ms and Error Rates Presented in Percent Error for All Conditions in Experiment 1 (Standard Errors Shown in Parentheses)

		Trial type		
		Switch trials	Nonswitch trials	Single task
Reaction time				
Group	Response compatibility			
Medicated	Compatible	2213 (217)	1987 (228)	828 (67)
	Incompatible	2274 (267)	2011 (222)	871 (69)
Unmedicated	Compatible	1967 (151)	1763 (254)	885 (57)
	Incompatible	2470 (257)	1775 (134)	915 (57)
Control	Compatible	1675 (189)	1532 (182)	727 (52)
	Incompatible	1917 (180)	1726 (198)	803 (89)
Error rate				
Group	Response compatibility			
Medicated	Compatible	1.5 (0.7)	2.6 (1.0)	0.0 (0.0)
	Incompatible	10.6 (2.8)	12.7 (3.3)	0.0 (0.0)
Unmedicated	Compatible	3.7 (2.1)	4.3 (1.8)	0.0 (0.0)
	Incompatible	18.7 (3.3)	17.6 (4.0)	0.0 (0.0)
Control	Compatible	2.5 (1.3)	3.6 (2.0)	0.0 (0.0)
	Incompatible	14.1 (2.8)	15.8 (3.3)	0.0 (0.0)

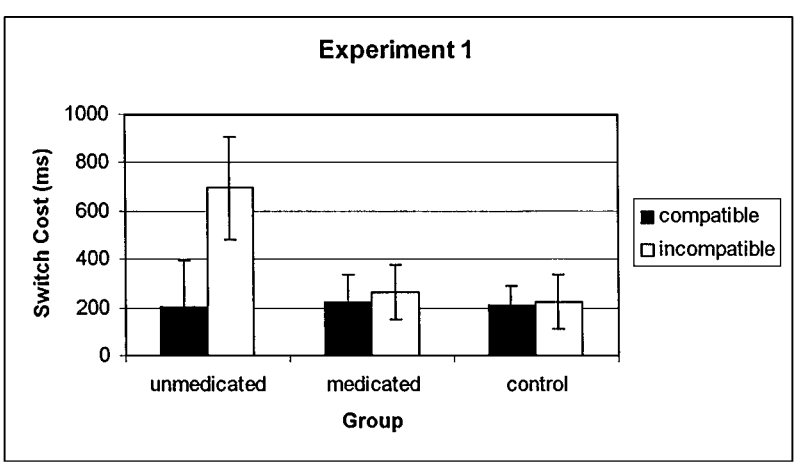

Fig. 2. Switch costs (switch costs = switch trial RT − nonswitch trial RT) for the ADHD and control children in Experiment 1.

($F(1, 15) = 26.2$, $p < .01$). The groups did not differ significantly on the error rate measure.

More important, however, was the significant two-way interaction between medication and trial type ($F(1, 15) = 6.1$, $p < .05$). Switch RT costs were larger for the ADHD children when they were unmedicated than when they were medicated. Although the three-way interaction between group, response compatibility, and trial type was not significant, the larger switch cost for the unmedicated than for the medicated ADHD children appears to be largely due to the performance difference in the incompatible response condition (Fig. 2). This issue will be addressed further in the discussion of Experiment 2.

In any event, it would appear that medication was helpful in assisting the ADHD children in the effective use of the control processes necessary for rapidly switching between the two tasks. Furthermore, the medication effect was quite selective. That is, medication did not significantly influence performance on the nonswitch trials, presumably because such trials place only minimal demands on executive control processes (Gopher, 1996; Kramer *et al.*, 1999; Rogers & Monsell, 1995; Rubinstein *et al.*, in press).

In our second set of ANOVAs, we contrasted the performance of the control children and the unmedicated ADHD children. Significant main effects were obtained

for compatibility for RT ($F(1, 15) = 15.3$, $p < .01$) and error rate ($F(1, 15) = 51.9$, $p < .01$) and for trial type ($F(1, 15) = 35.0$, $p < .01$) for RT. Subjects were faster and more accurate when responding on the compatible than on the incompatible trials. Subjects were also faster on the nonswitch than on the switch trials. More importantly, however, we obtained a significant two-way interaction between the trial type and group factors ($F(1, 15) = 5.6$, $p < .05$) for RT. This result is quite similar to that obtained for the contrast between the ADHD children on and off medication. ADHD children off medication appear to have more difficulty disengaging from one task and switching to another task than the same children on medication as well as control children.

In our third set of ANOVAs we contrasted the performance of the control children and the ADHD children on medication. Significant main effects were obtained for compatibility for RT ($F(1, 15) = 5.5$, $p < .05$) and error rate ($F(1, 15) = 31.3$, $p < .01$) and for trial type ($F(1, 15) = 13.0$, $p < .01$) for RT. Subjects were faster and more accurate when responding on the compatible than on the incompatible trials. Subjects were also faster on the nonswitch than on the switch trials. Unlike the previous sets of analyses, ADHD children on medication and control children did not differ in the magnitude of their switch costs (i.e., the interaction between trial type and group was not significant, $p > .75$). Thus, these results suggest that the executive control processes required to successfully perform the task-switching paradigm are just as efficient for ADHD children on medication as for non-ADHD control children. Tannock, Schachar, and Logan (1995; see also Tannock *et al.*, 1989) came to a similar conclusion on the basis of finding that medicated ADHD children were as effective at aborting a simple motor response as control children. The present results extend those obtained by Tannock *et al.* by showing that the medication benefits generalize beyond the inhibition of a simple motor response to the inhibition of choice responses and the preparation to perform another task.

Comparison of Nonswitch Trials in Single Task Blocks and Switch Blocks

In an additional set of analyses, we contrasted performance on the single-task blocks with performance on the nonswitch trials in the switch blocks for the medicated and unmedicated ADHD and control children. These data are presented in Table I for the mean RT and error rates. These analyses enabled us to ask whether the context in which identical (nonswitch) trials were performed would have a larger influence on unmedicated ADHD children than the medicated ADHD or control children. Assuming that the children would be more anxious and aroused on the switch blocks than on the single-task blocks (due to the greater task requirements on the switch blocks), resource allocation/arousal models of ADHD (Sergeant, 1995a,b; Zentall, 1985) would predict that performance would be differentially impaired for the ADHD children, even for the nonswitch trials, in the switch blocks. However, inhibition-based models of ADHD (Barkley, 1997; Pennington & Ozonoff, 1996; Schachar *et al.*, 1993, 1995; Quay, 1988, 1996) would not predict differential performance impairment for ADHD and control children in these situations given that neither task sets nor responses needed to be inhibited on the nonswitch trials.

In our first set of ANOVAs, we compared ADHD children on and off medication. A significant main effect was obtained for block type for RT ($F(1, 15) = 113.7$, $p < .01$) and error rate ($F(1, 15) = 24.6$, $p < .01$). RTs were faster and error rates were lower on the nonswitch trials in the single-task blocks than in the switch blocks. A significant two-way interaction was also obtained for the trial block and compatibility factors for error rate ($F(1, 15) = 18.4$, $p < .01$). Error rates were increased to a greater extent on the incompatible than the compatible nonswitch trials in the switch blocks. Interestingly, however, we failed to observe a significant main effect of medication or an interaction of the medication condition with task factors. Therefore, although context did influence performance, with better performance observed in the single-task blocks than in the switch blocks for the nonswitch trials, medication level did not modulate performance level.

Similar patterns of effects were obtained for our other two group comparisons. We obtained a significant main effect of block type for RT ($F(1, 15) = 37.3$, $p < .01$) and error rate ($F(1, 15) = 73.4$, $p < .01$) for the ANOVA that included control children and ADHD children off medication. A significant two-way interaction was also obtained for the block type and compatibility factors ($F(1, 15) = 34.8$, $p < .01$) for error rate. Error rates were highest for the incompatible trials on the switch blocks. The same effects were significant for the comparison of the ADHD children on medication and the control children. We obtained a significant main effect of block type for RT ($F(1, 15) = 60.1$, $p < .01$) and error rate ($F(1, 15) = 27.7$, $p < .01$) and a significant two-way interaction ($F(1, 15) = 21.9$, $p < .01$) for the block type and compatibility factors for error rate.

In summary, the analyses of the nonswitch trials indicated poorer performance in the switch blocks than in the single-task blocks, presumably due to the requirement to deal with increased complexity in the form of

maintaining multiple task sets in the switch blocks. Interestingly, the two ADHD groups (i.e., children on and off medication) and the control children showed equivalent performance costs for the nonswitch trials in the switch blocks as compared to performance in the single-task blocks. Thus, contrary to arousal/resource allocation models of ADHD (Sergeant, 1995a,b; Zentall, 1885) it would appear that both ADHD and non-ADHD children can cope effectively with task complexity per se. However, consistent with inhibition-based models of ADHD (Barkley, 1997; Pennington & Ozonoff, 1996; Schachar *et al.*, 1993, 1995; Quay, 1988, 1996), ADHD children, particularly when unmedicated, have greater difficulty in shifting dynamically between tasks than do non-ADHD children.

Experiment 2

The results of the first study established that unmedicated ADHD children have a specific difficulty in disengaging from one task and switching attention to another task. However, methylphenidate appears to abolish this performance decrement, consistent with other studies in the literature that have examined ADHD-related processing deficits in the inhibition of simple motor responses (Tannock *et al.*, 1989, 1995). That is, medicated ADHD children appear to be as efficient as non-ADHD children at inhibiting motor responses and switching dynamically between tasks.

Although this finding is important with regards to the proposal that ADHD results in a deficit in behavioral inhibition (Barkley, 1997), it is worth noting that in Experiment 1 the children could predict when a task switch would occur. That is, task switching occurred in a regular pattern, with a new task to be performed every third trial. However, this version of the task-switching paradigm differs in a number of ways from real-world situations that require switching between tasks or task components. For example, when riding a bicycle, a child must coordinate a number of tasks including lane tracking, monitoring for pedestrians and motor vehicles, and thinking about school or extracurricular activities. In many situations, the focus on one or several of these tasks must switch rapidly and unpredictably, often after performing one task for a considerable amount of time (e.g., having to swerve rapidly to avoid an automobile after pedaling for a considerable amount of time on a deserted roadway).

An important unanswered question is whether the results obtained in Experiment 1 will generalize to such a situation. That is, a situation in which task switches occur unpredictably, often after repeating a single task a multitude of times. Indeed, one might expect that both the inhibition of the previously performed task and the rapid preparation for the new task would be more difficult in such a situation, as compared to the situation examined in Experiment 1, with frequent and predictable task switches. Furthermore, given the often-reported difficulties that ADHD children have with tasks requiring such executive control processes (Barkley, 1989, 1997; Douglas, 1983; Schachar *et al.*, 1993; Seidman *et al.*, 1995), it is conceivable that larger and more robust switch costs might be obtained for unmedicated than for medicated ADHD children when task switches occur unpredictably and infrequently than when they occur predictably and often, as in Experiment 1.

In an effort to investigate this issue, we had ADHD children, on and off medication, perform in a task-switching paradigm in which a task switch would occur anywhere from four to eight trials following the previous switch. The main question was whether the influence of methylphenidate would be sufficient to reduce switch costs substantially with infrequent and unpredictable task switches, as had been the case with frequent and predictable switches in Experiment 1. An affirmative answer would provide more confidence that medication would be effective in enhancing the executive control processes necessary for the coordination of multiple tasks in real-world settings.

Within the context of the experimental design employed in the present study, we predicted a significant three-way interaction for the medication (ADHD children on and off medication), trial type (trial after a switch vs a later trial), and response compatibility (response-compatible vs response-incompatible trial) factors. That is, we predicted that unmedicated ADHD children would be much slower to respond following a task switch than task continuation, particularly when the the responses to the two tasks were incompatible, than the same children when medicated. This prediction is consistent with executive control models of ADHD. The enhanced switch cost with incompatible responses for the unmedicated ADHD children is anticipated given the unpredictable nature of the switches in the current paradigm (as compared to the predictable nature of the switches in Experiment 1), and therefore the need for greater executive control to inhibit the inappropriate response.

METHOD

Subjects

Twenty-two 6 to 12-year-old children with ADHD were run in this experiment. Subjects ranged in age from 6.7 to 12.5 years, and K-Bit composite scores ranged from

55 to 116. The average age was 10.6 years old and the average K-Bit composite score was 86.

The 22 ADHD children who participated in this study came from the same referral source and met the same clinical criteria for participation as the ADHD children in Experiment 1. Three of the children had also participated in Experiment 1. All of the children were positive for ADHD (DSM-III-R criteria) using the CDISC-P, and positive for ADHD (DSM-IV criteria) using the clinical assessment by the second author. Seventy-three percent (16/22) met DSM-IV criteria for ADHD, combined type, and 27% (6/22) for the hyperactive/impulsive type. The mean CTRS-28 Hyperkinesis Index off medication was 26 (range 18–30). The mean Hyperkinesis Index while using medication was 6 (range 0–12), for an average on-medication improvement of 20 points. Thirty-six percent (8/22) had been tested for possible MR or LD and did not qualify for such educational services (during the academic year following completion of the study, two children not previously tested did qualify for LD educational services). The median family income was $15,538 (range $6,948–$35,360). Fifty-five percent (12/22) were white and 45% (10/22) were African-American. Seventy-seven percent (17/22) of the children were male.

Children were tested twice, both on and off methylphenidate. Eleven children were unmedicated during the first session, and eleven were unmedicated during the second session.

Stimuli

The same stimuli were used as in Experiment 1.

Apparatus

The same apparatus was used as in Experiment 1.

Procedure

The basic procedure for administering the experiment did not differ from Experiment 1. The same general trial layout as in Experiment 1 was followed. The only major difference between Experiment 1 and Experiment 2 was that the task changed unpredictably after 3–7 trials during Experiment 2, rather than predictably every third trial, as in Experiment 1. In addition, no single-task only trials were run in the present study.

Five hundred experimental trials were run for each subject. Total time to complete the experiment was about 20–25 min.

RESULTS AND DISCUSSION

The mean RT and error rate data obtained in the present study are presented in Table II. The switch cost RTs are presented in Fig. 3. As can be seen from the data,

Table II. Reaction Times (RTs) Presented in ms and Error Rates Presented in Percent Error for All Conditions in Experiment 2 (Standard Errors Shown in Parentheses)

		Trial number following switch						
		1	2	3	4	5	6	7
Reaction time								
Group	Response compatibility							
Medicated	Compatible	1723	1555	1544	1533	1502	1488	1451
		(106)	(93)	(82)	(82)	(79)	(82)	(95)
	Incompatible	1838	1764	1634	1637	1626	1611	1475
		(82)	(101)	(78)	(74)	(86)	(94)	(68)
Unmedicated	Compatible	1749	1685	1719	1620	1586	1588	1561
		(116)	(118)	(122)	(118)	(110)	(147)	(100)
	Incompatible	2204	1883	1779	1736	1808	1724	1617
		(136)	(122)	(109)	(118)	(138)	(117)	(121)
Error rate								
Group	Response compatibility							
Medicated	Compatible	4.0	3.2	4.3	3.1	2.3	3.0	1.9
		(1.4)	(1.0)	(1.6)	(0.8)	(0.9)	(0.9)	(0.9)
	Incompatible	25.4	18.7	16.6	16.2	13.0	12.8	9.8
		(4.4)	(3.8)	(3.9)	(4.2)	(3.0)	(2.9)	(3.2)
Unmedicated	Compatible	4.2	4.8	5.1	4.9	4.4	5.6	1.5
		(1.0)	(1.4)	(1.5)	(1.6)	(1.6)	(1.6)	(0.8)
	Incompatible	29.2	19.0	16.1	15.5	16.1	16.6	12.6
		(3.8)	(3.5)	(3.2)	(2.8)	(3.4)	(3.4)	(3.2)

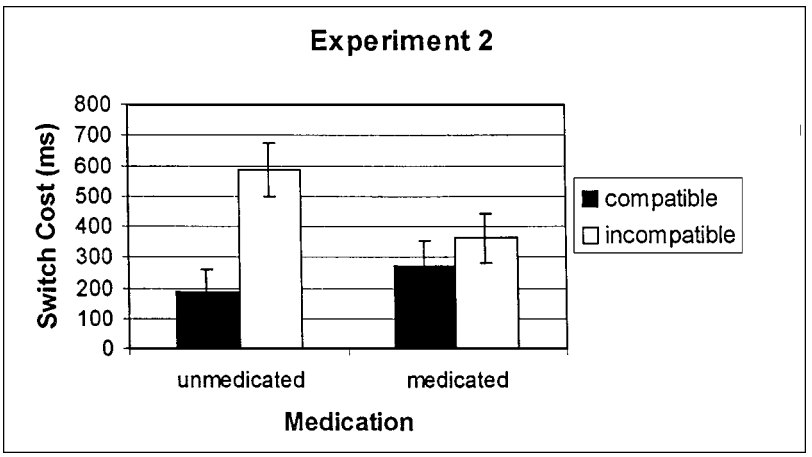

Fig. 3. Mean switch costs (switch cost = RT on the first trial following a switch − RT on the seventh trial following a switch) for the unmedicated and medicated ADHD children in Experiment 2.

a large switch cost is present on the first trial following a task switch, with substantially faster and more accurate performance on subsequent trials following a switch. It also appears that the compatibility effect (i.e., the difference in RT between incompatible and compatible response trials) interacts with the magnitude of the switch cost.

In order to quantify these observations we submitted the mean RT and error rate data to three-way ANOVAs with medication (on and off medication), trial type (first trial after the switch and seventh trial after a switch), and response compatibility as factors.[4] Significant main effects were obtained for compatibility for RT ($F(1, 21) = 9.6$, $p < .01$) and error rate ($F(1, 21) = 38.3$, $p < .01$) and for trial type for RT ($F(1, 21) = 37.7$, $p < .01$) and error rate ($F(1, 21) = 52.5$, $p < .01$). Responses were slower and less accurate for the trial after the switch than for the seventh trial after the switch and for the incompatible than for the compatible response trials.

Significant two-way interactions were obtained for RT ($F(1, 21) = 14.9$, $p < .01$) and error rate ($F(1, 21) = 46.7$, $p < .01$) for trial type × compatibility and for RT for compatibility × medication ($F(1, 21) = 6.1$, $p < .01$). RTs were slower and error rates were higher for the response incompatible than for the response compatible trials on the trial following a task switch than for subsequent trials. The compatibility effect was also larger for the ADHD children when unmedicated than when they were medicated. More important, however, was the significant three-way interaction for medication × trial type × compatibility for RT ($F(1, 21) = 7.0$, $p < .01$). As can be seen in Fig. 3, switch costs (i.e., switch costs = RT on the trial following a switch − RT on subsequent trials) were larger for the ADHD children when unmedicated on the incompatible response trials than for the same children when medicated.

In summary, the larger switch costs for the ADHD children when unmedicated than when medicated replicate and extend the results obtained in Experiment 1. It would appear that methylphenidate improves ADHD children's ability to inhibit inappropriate task procedures and prepare for a new task regardless of whether the task switch is frequent and predictable or infrequent and unpredictable.

The results from the present study also clarified the nonsignificant trend observed in Experiment 1 of the larger switch cost for the incompatible than for the compatible response trials for the unmedicated than for the medicated ADHD children. The present results suggest that switch costs are magnified, particularly for the unmedicated ADHD children, when the children must also attempt to suppress or inhibit an inappropriate response. This finding is consistent with previously reported difficulties that unmedicated ADHD children have in the Stroop task (Krener *et al.*, 1993; Pennington *et al.*, 1993; Seidman *et al.*, 1995), that is a task which requires that subjects respond to the color of the ink in which a word is printed and ignore the semantic content of the word. One interesting question

[4]We originally performed ANOVAs with seven levels of the trial type factors (i.e., trials 1–7 following a task switch). However, because the pattern of results for RT and error rate were essentially the same as those obtained with two levels of the trial type factor (first and seventh trial following a task switch), we report only the latter set of analyses here.

is why the interaction among medication, trial type, and compatibility was significant in the present study, but not in Experiment 1?

One possibility concerns the differences between the versions of the switch tasks employed in the two studies. The fact that task switches were infrequent and unpredictable in the present study likely made it more difficult for the children to inhibit the inappropriate responses, a speculation that is consistent with the substantially larger compatibility effects, particularly for the error rate measures, observed in the present study than in Experiment 1. This increased difficulty in inhibiting the inappropriate response could, in turn, reduce the amount of time available for the children to prepare for the new task, thereby magnifying the switch costs observed in the incompatible response trials. In any event, it does appear that situations in which it is difficult to inhibit inappropriate responses within trial coupled with situations that do not allow much advance preparation for the inhibition of inappropriate task procedures result in a magnification of switch costs, especially for unmedicated ADHD children. However, it also appears that methylphenidate can dramatically improve the efficiency of the necessary executive control processes in such situations.

GENERAL DISCUSSION

In the present studies, we employed the task-switching paradigm both to contrast two different classes of ADHD models, inhibition-based models, and resource allocation/arousal models, and to more finely delineate the nature of inhibitory deficits associated with ADHD. The task-switching paradigm, which has been relatively well studied in cognitive psychology (Allport *et al.*, 1994; Gopher, 1996; Jerslid, 1927; Kramer *et al.*, 1999; Merian, 1996; Rogers & Monsell, 1995; Rubinstein *et al.*, in press), offers a number of potential advantages over the more familiar WCST for the study of executive control processes of unmedicated and medicated ADHD children. First, both reaction time and error rate measures are obtained in the task-switching paradigm, therefore enabling the investigator to assess potential speed/accuracy tradeoffs between conditions or experimental groups. Only error rate measures are obtained in the WCST. Second, although subjects are left to discover the task rules in the WCST, the rules for performing the tasks are explicit and well known in the task-switching paradigm. Thus, the emphasis in the task-switching paradigm is on the examination of task reconfiguration processes—that is, those executive control processes that are needed for the inhibition of inappropriate task sets and responses as well as those control processes required for the preparation for a new task. In essence, the task-switching paradigm enables the investigator to focus on a subset of the executive control processes that are needed to perform the WCST task, therefore allowing one to more finely differentiate between those control processes that are adversely influenced by ADHD and those that are not adversely affected. Third, there is both psychometric (Kramer *et al.*, 1999) and experimental data (Gopher, 1996; Rogers & Monsell, 1995; Rubinstein *et al.*, in press), which suggests that executive control and component task processes (i.e., the perceptual, memory, and motor processes needed to perform the individual tasks) can be functionally dissociated in the task-switching paradigm. Thus, one is able to examine the influence of ADHD on these two sets of processes.

Indeed, the results obtained in our two studies suggest that performance on the individual tasks (i.e., in conditions in which a single task is performed repeatedly) is equivalent for ADHD children on and off medication as well as for non-ADHD control children. The performance deficits observed for the unmedicated ADHD children appear to be localized to the trial following a task switch; that is, the trial that entails the use of executive control processes necessary for response and task set inhibition and preparation to perform the new task (Gopher, 1996; Kramer *et al.*, 1999; Rogers & Monsell, 1995; Rubinstein *et al.*, in press). Thus, our data are consistent with models of ADHD that posit a central role for deficits in executive control and, more specifically, inhibitory processes (Barkley, 1997; Quay, 1988, 1996).

Our data, particularly those obtained in Experiment 2, also suggest that the difficulties that ADHD children have in coordinating the performance of multiple tasks are mainly the result of incompatibilities between the response requirements of the tasks. The ADHD children on medication and the control children performed equivalently on both the switch and nonswitch trials to the unmedicated ADHD children when the responses for the two tasks were compatible. However, switch costs were magnified for the ADHD as compared to the control children (and for the unmedicated as compared to the medicated ADHD children) on the response-incompatible trials. Thus, these data begin to establish boundary conditions on the nature of inhibitory deficits experienced in ADHD.

The data are also informative with regard to the cognitive mechanisms that underlie ADHD. The failure to find performance differences between ADHD and control children for the nonswitch trials in the single-task and switch blocks in Experiment 1 is inconsistent with predictions of the resource allocation/arousal models, especially because performance was less efficient for the nonswitch trials in the switch blocks. Such models would predict larger

differences between ADHD and control children in situations that result in higher arousal and resource requirements. However, inhibition-based models of ADHD do not predict performance differences between ADHD and non-ADHD children in such conditions, assuming that requirements to inhibit or suppress inappropriate responses or task sets remain constant.

Although the present studies have provided a number of important insights into information processing deficits exhibited by ADHD children in an aspect of common everyday situations—that is, the ability to rapidly and accurately switch priorities among different tasks—there are a number of other issues that can be examined within the context of the task-switching paradigm. For example, Kramer *et al.* (1999) found that old and young adults could perform equivalently in the task-switching paradigm (i.e., the switch costs for young and old adults were the same) after a moderate amount of practice, as long as each of the tasks was explicitly cued. However, when the subjects were required to keep track of the number of times that they had performed one task in order to decide when to switch to the other task (e.g., switch tasks after five repetitions of a task), then the young adults substantially outperformed the older adults. Thus, older adults had a particular difficulty executing the executive control processes required for task switching concurrently with a high working memory load task (i.e., keeping track of when to switch without the aid of an explicit cue). In the two studies reported in the present paper, the children were presented with explicit cues to indicate which task was to be performed. Given previous studies, it is conceivable that ADHD children might also have greater difficulties with an increased memory load (Barkley *et al.*, 1996; Douglas, 1988; Seidman *et al.*, 1995).

The delay between a cue that indicates a particular task is to be performed and the task-relevant stimuli may also play a role in the efficiency with which ADHD children are able to disengage from one task and switch to another task. As indicated above, Rogers and Monsell (1995) manipulated the response stimulus interval (RSI) between tasks from 150 to 1200 ms and found substantial decreases in switch costs as the RSIs increased from 150 to 600 ms but relatively stable switch costs between RSIs of 600 and 1200 ms. On the basis of these results, the authors concluded that two different executive control processes could be distinguished in the task-switching paradigm, an endogenous stagelike process of task reconfiguration, which can be carried out in anticipation of the stimulus, and an exogenous task reconfiguration process, which is triggered by the appearance of a stimulus associated with the task to be performed. Whether these two control processes are intact and equally efficient in ADHD and non-ADHD children (or medicated and unmedicated ADHD children) is an important topic for future research.

A future study might also include a dimensional analysis of the relationship between dose of medication (both as mg/kg and as absolute dose), behavioral improvement (based on Hyperkinesis Index scores), and performance on the task-switching paradigm or an alternative index of inhibitory processing. Such a study would entail repeated testing as medication is incrementally adjusted in order to calculate a dose–response curve for both behavioral responses in the classroom and performance on laboratory-based tests of executive control and inhibitory processing efficiency.

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