Effect of Methylphenidate on Motivation in Children With Attention-Deficit/Hyperactivity Disorder

Article *in* Experimental and Clinical Psychopharmacology · April 2011

DOI: 10.1037/a0022794 · Source: PubMed

7 authors, including:

John Chelonis
U.S. Food and Drug Administration
45 PUBLICATIONS **1,200** CITATIONS
SEE PROFILE

Sherry Ferguson
U.S. Food and Drug Administration
142 PUBLICATIONS **2,397** CITATIONS
SEE PROFILE

Merle G Paule
U.S. Department of Health and Human Services
342 PUBLICATIONS **6,070** CITATIONS
SEE PROFILE

Experimental and Clinical Psychopharmacology
2011, Vol. 19, No. 2, 145–153

DOI: 10.1037/a0022794

Effect of Methylphenidate on Motivation in Children With Attention-Deficit/Hyperactivity Disorder

John J. Chelonis
National Center for Toxicological Research and
University of Arkansas for Medical Sciences-Arkansas
Children's Hospital

Teresa A. Johnson
University of Arkansas for Medical Sciences-Arkansas
Children's Hospital

Sherry A. Ferguson and Kimberly J. Berry
National Center for Toxicological Research and
University of Arkansas for Medical Sciences-Arkansas
Children's Hospital

Brian Kubacak and Mark C. Edwards
University of Arkansas for Medical Sciences-Arkansas
Children's Hospital

Merle G. Paule
National Center for Toxicological Research and
University of Arkansas for Medical Sciences-Arkansas Children's Hospital

The effects of methylphenidate (MPH) on motivation were examined using a progressive ratio (PR) task in children who were prescribed MPH for the treatment of ADHD. Twenty-one children, 7 to 12 years of age, completed two test sessions, one under the effects of medication and one not. During each session, children pressed a lever to earn nickel reinforcers, where the first press resulted in a reinforcer and 10 additional presses were required for each subsequent reinforcer. Children on MPH had a significantly higher breakpoint than when off medication. This MPH-associated increase in the breakpoint manifested as a significant decrease in the interresponse times (IRT). Further, MPH administration resulted in a significant decrease in IRT variability. In contrast, MPH administration had no significant effects on the means and variability of postreinforcement pause duration. These results suggest that MPH increased motivation in children being treated for ADHD. Further, the inability of MPH to significantly reduce postreinforcement pause duration while simultaneously decreasing IRTs suggests that while MPH may increase motivation to perform an ongoing task, it may have little effect on the initiation of that task.

Keywords: motivation, progressive ratio, methylphenidate, Attention Deficit Hyperactivity Disorder, children

Attention-Deficit/Hyperactivity Disorder (ADHD) is one of the most common neurobehavioral disorders in childhood (Pastor & Reuben, 2008; Polanczyk, deLima, Horta, Biederman, & Rohde, 2007) and is characterized by developmentally inappropriate levels of inattention, impulsivity, and hyperactivity that are pervasive in more than one setting. Children with ADHD typically exhibit poor decision making that can lead to impulsive and risky behavior, have difficulty responding to cues from the behavior of others, are inept at taking turns, and have an impaired sense of time (Barkley, Fischer, Edelbrock, & Smallish, 1990; Barkley, Koplowitz, Anderson, & McMurray, 1997; DiScala, Lescoheir, Barthel, & Li, 1998; Gittelman, Mannuzza, Shenker, & Bonagura, 1985; Kerns, McInerney, & Wilde, 2001; Milberger, Biederman, Faraone, Chen, & Jones, 1997). Many of these maladaptive behaviors are thought to be the result of impairments in executive func-

John J. Chelonis, Sherry A. Ferguson, Kimberly J. Berry, and Merle G. Paule, Division of Neurotoxicology, National Center for Toxicological Research and Department of Pediatrics, University of Arkansas for Medical Sciences-Arkansas Children's Hospital; Teresa A. Johnson, Brian Kubacak, and Mark C. Edwards, Department of Pediatrics, University of Arkansas for Medical Sciences-Arkansas Children's Hospital.

This document has been reviewed in accordance with United States Food and Drug Administration (FDA) policy and approved for publication. Approval does not signify that the contents necessarily reflect the position or opinions of the FDA nor does mention of trade names or commercial products constitute endorsement or recommendation for use. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the FDA.

We thank Eric Allen, Richard Allen, Joe Meehan, and Martin Jackson for their assistance in managing the data, Richard Rassmussen for maintenance of the apparatus, and Donna Blake for conducting the study.

Correspondence concerning this article should be addressed to John J. Chelonis, Department of Pediatrics/CARE, AR Children's Hospital, 1 Children's Way, Slot 512-26, Little Rock, AR 72202. E-mail: john.chelonis@fda.hhs.gov

tions. Executive functions can be broadly described as behaviors that contribute to self-regulation, such as self-directed actions, organization of behavioral contingencies across time, use of self-directed speech, rules or plans, delaying gratification, working memory, and future oriented actions (see Barkley, 1997; Pennington & Ozonoff, 1996). Stimulant medication is a common pharmacological treatment for ADHD that can reduce many of the overt behavioral symptoms, as well as reduce executive function impairments (Kempton et al., 1999; Mayes, Bagwell, & Erkulwater, 2008; O'Driscoll et al., 2005; Pliszka et al., 2000; Wigal et al., 1999). For example, the administration of stimulant medication reduces the impairments in working memory (Chelonis et al., 2002; Kempton et al., 1999), time perception (Baldwin et al., 2004), future planning (Biederman et al., 2008; Kempton et al., 1999), and behavioral inhibition (Bedard et al., 2003; DeVito et al., 2009) that are often exhibited by children with ADHD.

Although a plethora of research has demonstrated that children with ADHD have a variety of impairments in executive functions and that stimulant medication can attenuate those impairments, the etiology of such executive function impairments remains unclear. One possibility is that these impairments result from deficits in motivation. In support of this hypothesis, some research has suggested that executive impairments may be attenuated, at least in part, by the administration of rewards (see Luman, Oosterlann, & Sargeant, 2005, for a review). For example, impairments in time perception (McInerney & Kerns, 2003) and response inhibition (Konrad, Gauggel, Manz, & Schöll, 2000) in children with ADHD can be attenuated with the use of positive reinforcers. Similar reinforcer effects on tasks measuring other executive functions have also been described (Carlson & Tamm, 2000; Douglas & Parry, 1983; Douglas & Parry, 1994). These results are consistent with a larger body of research demonstrating that children with ADHD exhibit motivational deficits (Carlson, Mann, & Alexander, 2000; Haenlein & Caul, 1987; Tripp & Wickens, 2008).

Children with ADHD are especially sensitive to manipulation of reinforcer parameters that affect the subjective value of those reinforcers. Specifically, manipulations of reinforcer parameters that decrease the value of a reinforcer disrupt performance in children with ADHD to a greater extent than control children (Douglas & Parry, 1994; Freibergs & Douglas, 1969; Parry & Douglas, 1983; Tripp & Alsop, 2001). Children with ADHD are especially sensitive to decreases in reinforcement rate (Douglas & Parry, 1994; Freibergs & Douglas, 1969; Parry & Douglas, 1983) and delays in reinforcement (Antrop et al., 2006; Neef et al., 2005; Rapport, 1986; Schweitzer & Sulzer-Azaroff, 1995; Solanto et al., 2001; Sonuga-Barke, Taylor, Sembi, & Smith, 1992). Taken together, these findings suggest that children with ADHD are more sensitive to variations in task parameters that affect motivation to perform a particular task.

One theory that has been proposed to explain the deficits in motivation exhibited in children with ADHD is the Elevated Reward Threshold Hypothesis (Haenlein & Caul, 1987). This theory suggests that task performance depends upon whether the subjective value of the reward for doing a task exceeds a minimum threshold. According to this theory, this minimum threshold is higher for children with ADHD than for children without ADHD. In other words, as the subjective value of a reward for engaging in a behavior increases, the point at which that reward will begin to reinforce behavior will occur sooner (at a lower subjective value) for children without ADHD than for children with ADHD. Similarly, as the subjective value of a reward for engaging in a behavior decreases, the point at which the reward no longer reinforces behavior will occur later (at a lower subjective value) for children without ADHD than for children with ADHD. One method used to decrease the subjective value of a reward is to decrease the rate of reward delivery by using partial reinforcement schedules. As predicted by the Elevated Reward Threshold Hypothesis the performance of children with ADHD on tasks in which partial reinforcement schedules are used tends to be impaired compared to that of children without ADHD, even though their performance is similar when continuous reinforcement is used (Douglas & Parry, 1994; Parry & Douglas, 1983).

Elements of this theory have more recently been incorporated into a neurobiological theory to describe the role of dopamine on the deficits observed in children with ADHD (Tripp & Wickens, 2008). According to this model, the deficits exhibited in children with ADHD are the result of altered firing patterns of dopamine neurons in these children. Specifically, this model suggests that children with ADHD are unable to form response-reinforcer associations that are similar in strength to those of children without ADHD. This is thought to result from a deficit in the ability of dopamine cells to fire in the presence of cues that are predictive of a reinforcer. This decrease in the firing of the dopamine cells at the time the response is made leads to a decrease in the excitatory value of engaging in that response, thus decreasing the motivation to engage in that response. This theory is supported by rodent studies that demonstrated that antagonism of these dopamine systems, either by lesions or drugs, leads to a decrease in motivation to perform specific behaviors (Aberman, Ward, & Salamone, 1998; Bezzina et al., 2008; Hamill, Trevitt, Nowend, Carlson, & Salamone, 1999; Roberts, 1989). Further, neuropsychological studies utilizing positron emission tomography in adults with ADHD have demonstrated that markers of dopamine synapses are reduced in the dopamine reward pathway (Volkow et al., 2009) and that methylphenidate enhances extracellular dopamine levels which may result in amplification of dopamine signals (Volkow, Fowler, Wang, Ding, & Gatley, 2002).

The purpose of this research was to directly assess the effects of methylphenidate (MPH) on motivation in children with ADHD using a progressive ratio task. Progressive ratio (PR) tasks measure motivation by requiring an organism to make responses to obtain reinforcers with the number of responses increasing with each reinforcer that is earned. PR tasks have been widely used to assess motivation in nonhuman and human subjects (Baron & Derenne, 2000; Hodos, 1961; Killeen, Posadas-Sanchez, Johansen, & Thrailkill,

2009; Paule, Chelonis, Buffalo, Blake, & Casey, 1999; Richardson & Roberts, 1996; Roane, 2008). Performance on PR tasks have been found to be sensitive to a variety of variables, such as level of food deprivation in appetitive tasks, quality and quantity of reinforcer, and reinforcer preference (Barbano, Le Saux, & Cador, 2009; Ferguson & Paule, 1997; Hodos, 1961; Hodos & Kalman, 1963; Keesey & Golstein, 1968; Roane, 2008; Skoldager, Pierre, & Mittleman, 1993). Rodent research has repeatedly demonstrated that dopamine depletion decreases performance on PR tasks (Aberman, Ward, & Salamone, 1998; Bezzina et al., 2008; Hamill et al., 1999; Roberts, 1989; Salamone, Correa, Mingote, Weber, & Farrar, 2006; Wise, 2004). One study conducted in children with ADHD found that MPH enhanced performance on a PR task (Wilkison, Kircher, McMahon, & Sloane, 1995). This task required children to press a button to turn off a stimulus light that remained illuminated until the button was pressed. After an effective response, the stimulus light was reilluminated after one second. The child earned a reinforcer (two pennies) after the stimulus light was turned off for the first time, and the number of times the stimulus light had to be turned off increased by four button presses for every subsequent reinforcer that was earned. The child could make a maximum of 5100 responses during a 2-hour session but could terminate the session at any time.

The present research expands upon that study by using a free operant procedure rather than a signaled trials procedure making it more similar to the PR procedures that have been used in a variety of behavioral and pharmacological studies (see Hodos, 1961; Killeen, Posadas-Sanchez, Johansen, & Thrailkill, 2009; Richardson & Roberts, 1996). Requiring the child to make a response to turn off a light on each trial in the Wilkison et al. (1995) study may have served to increase motivation to make responses because the light may have served as an aversive stimulus that indicated no reinforcer would be delivered, and the act of turning the light off could have served as a conditioned reinforcer. In addition to reducing the reinforcing effects that occur in a trials procedure, allowing the subject to respond at their own pace throughout the session provides an opportunity for a more detailed analysis of the data, such as an examination of postreinforcement pause duration and interresponse times. Most research utilizing PR procedures have only reported breakpoint, as was the case for the Wilkison et al. (1995) study, or in rare instances, overall response rate and perhaps postreinforcement pause duration (see Killeen et al., 2009). Data for the mean interresponse time, mean post reinforcement pause duration, as well as the variability of both of these measures are reported here, thus providing a unique opportunity to examine these individual processes in detail.

The present study also expands upon the findings of the Wilkison et al. (1995) study by utilizing a different reinforcement rate. Specifically, the children in the present study earned 5 cents during each reinforcer delivery and the ratio required increased by 10 lever presses, whereas children earned 2 cents in the Wilkison et al. study and the ratio required increased by 4 button presses. Finally, the present study used a 10-minute session during which a maximum of 4380 responses could be made and the child could earn at most $1.50, whereas in the previous study participants could continue the task for up to 2 hours, make 5100 responses, and earn at most $1.00. The use of a 10-minute session rather than a 2-hour session allows for the rapid assessment of motivation and provides the opportunity for this test to be incorporated into a battery of tests (Paule et al., 1999).

Given that previous research has found that the administration of stimulant medication enhanced performance in children with ADHD using a 2-hour, trial based PR procedure (Wilkison et al., 1995), we hypothesized that it would also significantly enhance performance in children with ADHD on a brief free-operant procedure. According to the Elevated Reward Threshold Hypothesis (Haenlein & Caul, 1987) and the neurobiological theory regarding deficits in dopamine transfer (Tripp & Wickens, 2008), stimulant medication should increase the strength of the response-reinforcer associations, thus increasing the subjective value of the reinforcer and, in turn, making the reinforcer less sensitive to discounting following a delay. Therefore, we hypothesized that the administration of stimulant medication should decrease the duration of the postreinforcement pause because the delayed reinforcer will have more subjective value when children with ADHD are on medication than off medication. This is supported by research demonstrating that postreinforcement pause duration is affected by the size of the ratio to be completed rather than the size of the ratio that was previously completed (Crossman, 1968; Mintz, Mourer, & Gofseyeff, 1967). Hence, any manipulation that can attenuate the decrease in the subjective value of a reinforcer following a delay should facilitate the initiation of a response for that reinforcer. Further, because the subjective value of the reinforcer has been increased, it is hypothesized that the interresponse times will be shorter because the child will be more likely to stay on task following the administration of stimulant medication. Finally, we hypothesized that the administration of stimulant medication would significantly decrease the variability of both the interresponse time and the post reinforcement pause duration because previous research has demonstrated that the administration of stimulant medication can decrease variability of performance on other tasks (Baldwin et al., 2004; Spencer et al., 2009).

Methods

Participants

The participants were 21 children, 17 males and 4 females, who were recruited from outpatient clinics at the Arkansas Children's Hospital in Little Rock, Arkansas. The participants were greater than or equal to 7 years but less than 12 years of age ($M = 9.24$, $SD = 1.14$). Informed consent was obtained from one or both parents and assent was obtained from each child. Children were included in this study if they had a *t*-score greater than 65 on the hyperactive subscale of the parent's version of the Conner's ADHD/*DSM–IV* Scale (CADS; Conners, 1997) and had a current prescription from a physician for methylphenidate (MPH) for the treatment of ADHD. Twenty of these chil-

dren also had a t-score of greater than 65 on the inattention subscale of the CADS and the remaining child had a score of 64. All children met *DSM–IV* criteria for ADHD based on an interview by a child psychologist, psychiatrist, or pediatrician that was conducted as part of the child's evaluation prior to treatment. All children in this study also had a composite intelligence score greater than 70 ($M = 101.47$, $SD = 15.39$), as measured by the Kaufman Brief Intelligence Test (KBIT; Kaufman & Kaufman, 1990), and did not meet criteria for schizophrenia or pervasive developmental disorder, as measured by the Child Symptom Inventory (CSI; Gadow & Sprafkin, 1997). Nine participants met criteria for oppositional defiant disorder, five participants met criteria for conduct disorder, and one participant met criteria for major depressive disorder based on the Child Symptom Inventory (CSI; Gadow & Sprafkin, 1997).

All children participated in two experimental sessions that were separated by at least one week but not more than six weeks ($M = 25.52$ days, $SD = 9.19$). One test session occurred more than one hour but less than two hours after the child had taken their prescribed dose of MPH (on MPH). The other test session occurred at least 18 hours after the child had taken his or her last prescribed dose of MPH (off MPH). The order of these sessions was randomly assigned: nine children participated in their first session off MPH, and the other 12 participated in their first session on MPH. Nine children received 10 mg, 3 received 15 mg, and 3 received 20 mg of either Ritalin or generic methylphenidate. One child received 27 mg, two received 36 mg, and three received 54 mg of Concerta. The doses ranged from 0.20 to 0.88 mg/kg for Ritalin and generic methylphenidate and 0.52 to 1.39 mg/kg for Concerta. The dose of Concerta was calculated the same way as for Ritalin and generic methylphenidate, by dividing the total dose of medication consumed by the weight of the child.

Apparatus

Participants performed the Progressive Ratio (PR) task in a sound-attenuated room that measured 2.4 by 2.4 m that was illuminated throughout the entire session by fluorescent ceiling lights. The child's behavior was continually monitored by the experimenter through a one-way mirror located on one wall. A TV monitor that was used to present an instructional videotape with specific audio and visual directions was located on a table placed against the opposite wall from the one-way mirror. The experimental apparatus was attached to the center of the wall adjacent to the table and consisted of a large wooden cabinet, 182 cm tall by 60.8 cm wide by 50.4 cm deep. A response panel and a nickel dispenser were mounted on the front of this cabinet. Figure 1 shows a caricature of the response panel (55.6 cm high × 65.4 cm wide) located on the front of the apparatus 60.8 cm above the floor. A round speaker (6 cm in diameter) was located 7.3 cm below the top edge of the panel. The panel contained two types of response manipulanda and a variety of stimulus lights. The response manipulanda used for the PR task was the far right of four retractable response levers located 35.5 cm below the bottom edge of the speaker. Each response lever was 5 cm wide and could be extended 3 cm from the apparatus. The response levers were centered in a horizontal row, each 3.5 cm apart. Positioned 22 cm below the response panel and 15 cm from the left edge of the apparatus was a tray (15 cm wide, 10 cm deep, and7.5 cm high) into which reinforcers (nickels) were delivered. The stimulus lights and other manipulanda on the response panel were not used during the PR task. The presentation of stimuli and recording of responses were automated using a behavioral control system developed at the National Center for Toxicological Research.

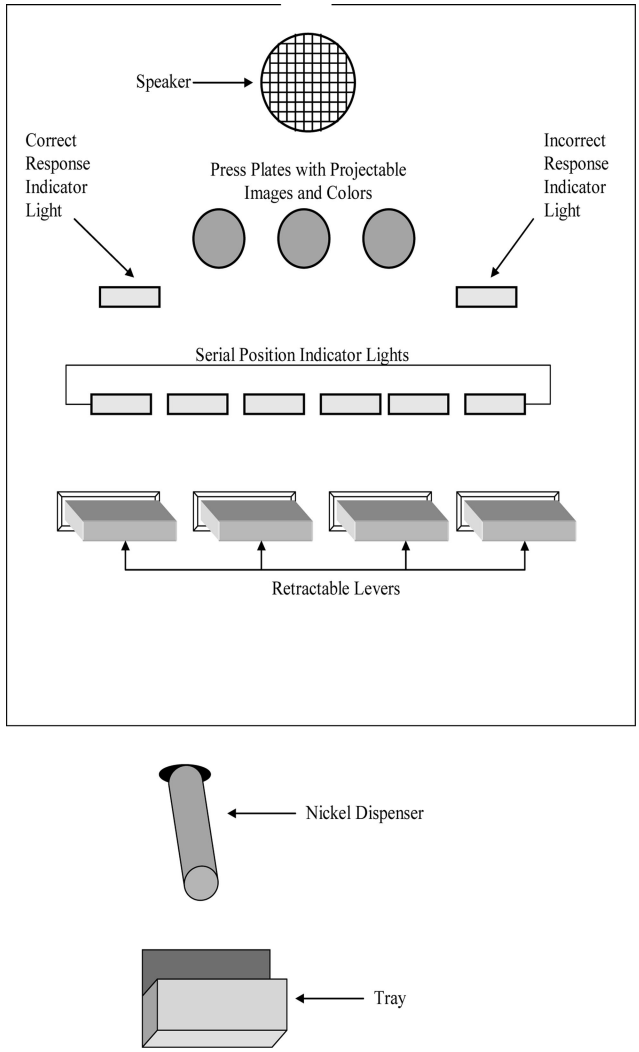

Figure 1. Diagram of apparatus. Only the far right retractable response lever was used. The tube and tray indicate where nickels were dispensed.

Procedure

Upon arriving for the first test session, the parent completed several forms containing demographic questions and the child's physical and educational history. The experi-

menter escorted the child from the waiting area to the testing room containing the TV monitor, chair, and the experimental apparatus. The experimenter told the child that he or she would play five games (tasks) that would take a total of approximately 1-hour to complete and that instructions for each game would be shown on the TV monitor prior to each game. Although five tasks were performed during each test session, only the procedure and data from the PR task are reported here. The other tasks are described in detail elsewhere (Paule, Cranmer, Wilkins, Stern, & Hoffman, 1988).

After the child entered the testing room, the experimenter started the videotaped instructions for the PR task and left the room. The audio portion of the instructions was:

> Notice on the panel in front of you here [the narrator points to the panel] that there are four levers toward the bottom [the narrator points to the levers]. In this game the lever on your far right, here, [the narrator points to the right-most lever] will come out of the machine [right-most lever extends from the machine]. When you see the lever come out, you should then begin pressing the lever, like this [the narrator presses the lever repeatedly]. When you press the lever enough times you will receive a nickel [a nickel dispenses from the machine and narrator stops pressing the lever]. Continue pressing [the narrator presses the lever repeatedly] the lever as long as you want to continue receiving nickels [a nickel dispenses from the machine and the narrator stops pressing the lever]. You can quit whenever you like but remember, the more you press [the narrator presses the lever repeatedly], the more nickels that you get [a nickel dispenses from the machine and the narrator stops pressing the lever]. When the game is over, the lever will go back in to the machine [the lever retracts into the machine].

When the videotaped instructions ended, the experimenter reentered the testing room and asked if the child understood the instructions. Children consistently stated they understood the instructions and required no further explanation of the task. After the child stated that he or she understood the instructions, the experimenter left the testing room, closed the door, and initiated the task. The experimenter did not interact with the child during the entire PR test session.

The task began when the right response lever was extended from the panel. Lever presses were reinforced with a nickel based on a PR 1 + 10 schedule. In other words, after the first lever press, a nickel was delivered. The number of lever presses required to obtain each subsequent nickel was increased by 10. Thus, the first reinforcer "cost" 1 lever press, the second cost 11 lever presses, the third 21, and so forth. The task continued until 30 nickels were earned or 10 minutes had elapsed.

During each 1-hour test session, participants performed five different tasks in the following order: PR (10 min), conditioned position responding (5 min), temporal response differentiation (10 min), delayed matching-to-sample (15 min), and incremental repeated acquisition (15 min). Each child was offered a 1 to 2-minute break between tasks. Each participant's nickels were counted at the end of the test session and supplemented as necessary to insure that each child received a minimum of five dollars for the entire session. After the five tasks were completed on the first test session, the Kaufman Brief Intelligence Test was administered. Once all the tests had been completed, the experimenter escorted the child back to his or her parent.

Results

Performance on the PR task was not significantly different between the first and second session, as measured by breakpoint, regardless of whether the two sessions were being compared off medication, $t(19) = 1.06$, $p = .30$, or on medication, $t(19) = -0.78$, $p = .45$. Given the lack of significant order effects, the data for the two orders were collapsed for all analyses. Table 1 shows the means and standard errors for the medication and no medication conditions for each of the dependent variables: breakpoint, mean interresponse time (IRT), mean postreinforcement pause duration, variability (standard deviation) of IRT, and variability (standard deviation) of postreinforcement pause duration. This table also shows the results of t-tests comparing performance for each variable on and off medication as well as the effect size (Cohen's *d*). Breakpoint is defined as the largest ratio the participant completed. IRTs were defined as the time in seconds between each lever press, excluding the latency to the initial response during the session and the time between the last response before a reinforcer was delivered and the first response following a reinforcer. Postreinforcement pause duration was defined as the time in seconds between the last response before a reinforcer was delivered and the first response following a reinforcer. The table reveals that the administration of stimulant medication resulted in significantly higher breakpoints and significantly shorter IRTs. The significant decrease in mean IRTs appears to be the result of a significant decrease in the variability of IRTs observed following the administration of stimulant medication. Conversely, the administration of stimulant medication had no significant effect on the mean or variability of postreinforcement pause duration. Regardless of MPH status, children had significantly longer postreinforcement pause duration than IRTs: on medication, $t(20) = 6.27$, $p < .01$, and off medication, $t(20) = 3.35$, $p < .01$. When children were on medication, they tended to have a greater amount of variability in their postreinforcement pause duration than in their IRT duration, $t(20) = 2.03$, $p = .05$. This trend was not present when children were off medication, $t(20) = 0.83$, $p = .42$.

Table 1
Summary of Dependent Variables

	On MPH	Off MPH	
	M (*SE*)	*M* (*SE*)	*t* (*d*)
Breakpoint	199.10 (4.56)	189.10 (5.19)	2.65 (0.46)*
Mean IRT	0.27 (0.01)	0.30 (0.02)	−3.31 (0.46)**
Mean PRP	1.47 (0.20)	1.43 (0.34)	0.10 (0.03)
Variability IRT	0.25 (0.09)	0.53 (0.18)	−2.81 (0.45)**
Variability PRP	1.58 (0.71)	1.63 (1.32)	−.04 (0.03)

Note. PRP = Post-reinforcement pause duration.
* $p < .05$. ** $p < .01$.

Table 2 shows the correlations between the dependent variables when children with ADHD were on stimulant medication (1a) and off stimulant medication (1b). When children with ADHD were on stimulant medication, all but one of the dependent variables were significantly correlated with the absolute value of the correlations ranging from .55 to .95. The absolute correlation between the mean of interresponse time and the variability of postreinforcement pause duration was .42, which was nearly significant, $p = .057$. In contrast, for children with ADHD off medication, four of the correlations were significant whereas six were not. In fact, some of the correlations were quite low, even though they were significant when the children were on medication.

Discussion

The effects of methylphenidate (MPH) on motivation in children with ADHD were assessed using a progressive ratio (PR) schedule of positive reinforcement (nickels). When children were on MPH, they had a higher breakpoint. This finding is similar to that observed after stimulant medication administration using a PR task with different parameters (Wilkison et al., 1995) and allows for the generalization of these findings to PR tasks that are commonly used to assess motivation across species. This finding is also consistent with the literature linking dopaminergic activity with motivation (Aberman, Ward, & Salamone, 1998; Bezzina et al., 2008; Hamill et al., 1999; Roberts, 1989), as well as the research suggesting that the motivational deficits observed in children with ADHD result from abnormalities in the functioning of the dopamine system (Tripp & Wickens, 2008; Volkow et al., 2002; Volkow et al., 2009).

The enhanced PR responding following MPH administration was associated primarily with a decrease in interresponse times (IRT), whereas postreinforcement pause duration was not sensitive to MPH treatment. That MPH did not yield similar effects on postreinforcement pause duration as observed for IRTs is interesting because it suggests that these variables are sensitive to different manipulations. Specifically, dopaminergic drugs, such as MPH, may affect IRTs with relatively little effect on postreinforcement pause duration as seen here while nondopaminergic drugs (e.g., atomoxetine) might have different effects. This finding may also be difficult to explain in the framework of the Dopamine Transfer Deficit theory (Tripp & Wickens, 2008) because, in its present form, this theory does not describe to which specific reinforcer-associated cues or responses the dopamine response will be transferred. Similarly, the Elevated Reward Threshold Hypothesis (Haenlein & Caul, 1987) suggests that stimulant medication will cause a general decrease in the reward threshold leading to a global increase in the ability to form response-reinforcer associations. The fact that the IRTs in the present study decreased whereas the postreinforcement pause duration did not suggests that the responses during the run were strengthened while the strength of the initial response, prior to the start of the run, remained relatively stable. The inability of MPH to decrease the postreinforcement pause duration was especially surprising given that delayed reinforcers typically have less subjective value for children with ADHD (Antrop et al., 2006; Neef et al., 2005; Rapport, 1986; Schweitzer & Sulzer-Azaroff, 1995; Solanto et al., 2001; Sonuga-Barke et al., 1992) and that stimulant medication has been reported to decrease the aversiveness of delays in these children (Shiels et al., 2009). The fact that the MPH administration had different effects on IRTs and postreinforcement pause duration suggests that the processes underlying these two aspects of PR responding are separate and distinct. In addition, the inability of MPH to significantly reduce postreinforcement pause duration while simultaneously decreasing IRTs suggests that MPH may increase motivation to perform an ongoing task but may have little effect on the task initiation. Further evidence that these processes are different can be found in the lack of a significant correlation of these dependent variables when children were off medication, although the correlation was significant when these same children were on medication.

The present results also indicated that MPH administration significantly reduced the variability of the IRTs. Specifically, MPH administration reduced the number of long duration IRTs, resulting in a decrease in variability as well as a decrease in the mean duration of the IRTs. This suggests that MPH administration increased the consistency of the rate at which children pressed the lever. Further, this decrease in the variability of IRTs suggests that MPH enhanced the ability of the children to stay on task once a response run (i.e., the responses between one reinforcer and the next) was initiated. This finding is consistent with results demonstrating that stimulant medication decreases the variability of lever hold duration on a time production task (Baldwin et al., 2004). In contrast, MPH administration had relatively little effect on the variability of postreinforcement pause duration. Here again, the administration of MPH had different effects on the variability of IRT and postreinforcement pause duration providing further evidence that these are separate and distinct processes. Further, the lack of significant correlations between these dependent variables when children were off medication is evidence that they

Table 2
Correlations Between Dependent Variables

	Mean IRT	Mean PRP	Variability IRT	Variability PRP
a) On MPH				
Breakpoint	0.95***	0.68***	0.59**	0.55**
Mean IRT	—	0.57***	0.55**	0.42
Mean PRP		—	0.57**	0.91***
Variability IRT			—	0.65**
b) Off MPH				
Breakpoint	0.94***	0.31	0.49*	0.21
Mean IRT	—	0.08	0.53**	0.02
Mean PRP		—	0.01	0.98***
Variability IRT			—	0.01

Note. PRP = Post-reinforcement pause duration.
* $p < .05$. ** $p < .01$. *** $p < .001$.

are separable processes, even though the correlations were significant when these same children were on medication.

While these data support our hypothesis that MPH administration increases motivation in children with ADHD, there are some limitations to this study. First, the lack of a placebo does not allow the expectation associated with medication to be ruled out as a possible explanation for these results. However, this explanation is unlikely because a placebo was used in the Wilkison et al. (1995) study, and they also found significant improvements on their motivation task following the administration of medication. Second, the lack of specific dose conditions precludes the direct examination of a dose-response relationship between MPH and motivation. The fact that motivation was assessed during a single session under a relatively wide range of doses across participants may have increased the intraparticipant variability observed during their MPH condition. In addition, the inclusion of a control group would have been helpful to determine the extent to which children with ADHD exhibit impairments on this task and the extent to which MPH normalizes performance in these children. It would also have been interesting to compare the motivation effect of MPH using the PR task with other measures of motivation, such as independent observations or questionnaire measures. Although the data from the PR session suggests that MPH enhanced motivation by reducing if not eliminating off-task behavior, observations of the child during the session would have been useful to confirm to what extent this did occur.

In conclusion, the current findings provide additional support for the ability of stimulant medication to enhance performance on a wide variety of tasks (Baldwin et al., 2004; Biederman et al., 2008; Chelonis et al., 2002; Kempton et al., 1999). These results are also consistent with a model in which stimulant medication enhances motivation and, in turn, improves performance on other tasks measuring executive functions. For example, many of these same children were assessed on and off stimulant medication using a delayed matching-to-sample task, which is commonly used to assess working memory. The results indicated a significant decrease in choice response latencies and a significant increase in accuracy following long delays when on medication (Chelonis et al., 2002). This is consistent with the model above because MPH administration enhanced motivation in children with ADHD to stay on task, which resulted in an improvement on this executive function task.

The present research also suggests that studies utilizing a PR task as a motivational measure should examine postreinforcement pause duration and IRTs independently rather than focusing solely on more global variables, such as response rate or breakpoint, because postreinforcement pause duration and IRTs seem to be distinct variables. Finally, the current findings demonstrate that a brief PR task can effectively detect differences in aspects of motivation, allowing for rapid assessment and making it a candidate for the inclusion in various test batteries or for use in clinical settings.

References

Aberman, J. E., Ward, S. J., & Salamone, J. D. (1998). Effects of dopamine antagonists and accumbens dopamine depletions on time-constrained progressive-ratio performance. *Pharmacology, Biochemistry, and Behavior, 61*(4), 341–348.

Antrop, I., Stock, P., Verté, S., Wiersema, J. R., Baeyens, D., & Roeyers, H. (2006). ADHD and delay aversion: The influence of non-temporal stimulation on choice for delayed rewards. *Journal of Child Psychology and Psychiatry, 47*(11), 1152–1158.

Baldwin, R. L., Chelonis, J. J., Flake, R. A., Edwards, M. C., Feild, C. R., Meaux, J. B., & Paule, M. G. (2004). Effect of methylphenidate on time perception in children with Attention-Deficit/Hyperactivity Disorder. *Experimental and Clinical Psychopharmacology, 12*(1), 57–64.

Barbano, M., Le Saux, M., & Cador, M. (2009). Involvement of dopamine and opioids in the motivation to eat: Influence of palatability, homeostatic state, and behavioral paradigms. *Psychopharmacology, 203*(3), 475–487.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*(1), 65–94.

Barkley, R. A., Fischer, M., Edelbrock, C., & Smallish, L. (1990). The adolescent outcome of hyperactive children diagnosed by research criteria: I. An 8-year prospective follow-up study. *Journal of the American Academy of Child & Adolescent Psychiatry, 29*(4), 546–557.

Barkley, R. A., Koplowitz, S., Anderson, T., & McMurray, M. B. (1997). Sense of time in children with ADHD: Effects of duration, distraction, and stimulant medication. *Journal of the International Neuropsychological Society, 3*(4), 359–369.

Baron, A., & Derenne, A. (2000). Progressive-ratio schedules: Effects of later schedule requirements on earlier performances. *Journal of the Experimental Analysis of Behavior, 73*(3), 291–304.

Bedard, A. C., Ickowicz, A., Logan, G. D., Hogg-Johnson, S., Schachar, R., & Tannock, R. (2003). Selective inhibition in children with Attention-Deficit Hyperactivity Disorder off and on stimulant medication. *Journal of Abnormal Child Psychology, 31*(3), 315–327.

Bezzina, G., den Boon, F. S., Hampson, C. L., Cheung, T. H., Body, S., Bradshaw, C. M., . . . Deakin, J. F. W. (2008). Effect of quinolinic acid-induced lesions of the nucleus accumbens core on performance on a progressive ratio schedule of reinforcement: Implications for inter-temporal choice. *Psychopharmacology, 197*(2), 339–350.

Biederman, J., Seidman, L. J., Petty, C. R., Fried, R., Doyle, A. E., Cohen, D. R., . . . Faraone, S. V. (2008). Effects of stimulant medication on neuropsychological functioning in young adults with attention-deficit/hyperactivity disorder. *Journal of Clinical Psychiatry, 69*(7), 1150–1156.

Carlson, C. L., Mann, M., & Alexander, D. K. (2000). Effects of reward and response cost on the performance and motivation of children with ADHD. *Cognitive Therapy and Research, 24*(1), 87–98.

Carlson, C. L., & Tamm, L. (2000). Responsiveness of children with attention deficit–hyperactivity disorder to reward and response cost: Differential impact on performance and motivation. *Journal of Consulting and Clinical Psychology, 68*(1), 73–83.

Chelonis, J. J., Edwards, M. C., Schulz, E. G., Baldwin, R., Blake, D. J., Wenger, A., & Paule, M. G. (2002). Stimulant medication improves recognition memory in children diagnosed with attention-deficit/hyperactivity disorder. *Experimental and Clinical Psychopharmacology, 10*(4), 400–407.

Conners, K. (1997). Conners' Rating Scales-Revised. Toronto, Canada: Multi-Health Systems.

Crossman, E. K. (1968). Pause relationships in multiple and chained fixed-ratio schedules. *Journal of Experimental Analysis of Behavior, 48,* 395–406.

DeVito, E. E., Blackwell, A. D., Clark, L., Kent, L., Dezsery, A. M., Turner, D. C., . . . Sahakian, B. J. (2009). Methylphenidate improves response inhibition but not reflection-impulsivity in children with attention deficit hyperactivity disorder (ADHD). *Psychopharmacology, 202*(1–3), 531–539.

DiScala, C., Lescohier, I., Barthel, M., & Li, G. (1998). Injuries to children with Attention Deficit Hyperactivity Disorder. *Pediatrics, 102*(6), 1415.

Douglas, V. I., & Parry, P. A. (1983). Effects of reward on delayed reaction time task performance of hyperactive children. *Journal of Abnormal Child Psychology, 11*(2), 313–326.

Douglas, V. I., & Parry, P. A. (1994). Effects of reward and nonreward on frustration and attention in attention deficit disorder. *Journal of Abnormal Child Psychology, 22*(3), 281–302.

Ferguson, S. A., & Paule, M. G. (1997). Progressive ratio performance varies with body weight in rats. *Behavioural Processes, 40*(2), 177–182.

Freibergs, V., & Douglas, V. I. (1969). Concept learning in hyperactive and normal children. *Journal of Abnormal Psychology, 74*(3), 388–395.

Gadow, K. D., & Sprafkin, J. (1997). *Child Symptom Inventory-4: Norms manual*. Stony Brook, NY: Checkmate Plus.

Gittelman, R., Mannuzza, S., Shenker, R., & Bonagura, N. (1985). Hyperactive boys almost grown up: I. Psychiatric status. *Archives of General Psychiatry, 42*(10), 937–947.

Haenlein, M., & Caul, W. F. (1987). Attention Deficit Disorder with Hyperactivity: A specific hypothesis of reward dysfunction. *Journal of the American Academy of Child & Adolescent Psychiatry, 26*(3), 356–362.

Hamill, S., Trevitt, J. T., Nowend, K. L., Carlson, B. B., & Salamone, J. D. (1999). Nucleus accumbens dopamine depletions and time-constrained progressive ratio performance: Effects of different ratio requirements. *Pharmacology, Biochemistry and Behavior, 64*(1), 21–27.

Hodos, W. (1961). Progressive ratio as a measure of reward strength. *Science, 134*(3483), 943–944.

Hodos, W., & Kalman, G. (1963). Effects of increment size and reinforcer volume on progressive ratio performance. *Journal of the Experimental Analysis of Behavior, 6*(3), 387–392.

Kaufman, A. S., & Kaufman, N. L. (1990). *Kaufman Brief Intelligence Test*. Circle Pines, MN: American Guidance Services.

Keesey, R. E., & Goldstein, M. D. (1968). Use of progressive fixed-ratio procedures in the assessment of intracranial reinforcement. *Journal of the Experimental Analysis of Behavior, 11*(3), 293–301.

Kempton, S., Vance, A., Maruff, P., Luk, E., Costin, J., & Pantelis, C. (1999). Executive function and Attention Deficit Hyperactivity Disorder: Stimulant medication and better executive function performance in children. *Psychological Medicine: A Journal of Research in Psychiatry and the Allied Sciences, 29*(3), 527–538.

Kerns, K. A., McInerney, R. J., & Wilde, N. J. (2001). Time reproduction, working memory, and behavioral inhibition in children with ADHD. *Child Neuropsychology, 7*(1), 21–31.

Killeen, P. R., Posadas-Sanchez, D., Johansen, E., & Thrailkill, E. A. (2009). Progressive ratio schedules of reinforcement. *Journal of Experimental Psychology: Animal Behavior Processes, 35*(1), 35–50.

Konrad, K., Gauggel, S., Manz, A., & Schöll, M. (2000). Lack of inhibition: A motivational deficit in children with attention deficit/hyperactivity disorder and children with traumatic brain injury. *Child Neuropsychology, 6*(4), 286–296.

Luman, M., Oosterlaan, J., & Sergeant, J. A. (2005). The impact of reinforcement contingencies on AD/HD: A review and theoretical appraisal. *Clinical Psychology Review, 25*(2), 183–213.

Mayes, R., Bagwell, C., & Erkulwater, J. (2008). ADHD and the rise in stimulant use among children. *Harvard Review of Psychiatry, 16*(3), 151–166.

McInerney, R. J., & Kerns, K. A. (2003). Time reproduction in children with ADHD: Motivation matters. *Child Neuropsychology, 9*(2), 91–108.

Milberger, S., Biederman, J., Faraone, S. V., Chen, L., & Jones, J. (1997). Further evidence of an association between attention-deficit/hyperactivity disorder and cigarette smoking: Findings from a high-risk sample of siblings. *The American Journal on Addictions, 6*(3), 205–217.

Mintz, D. E., Mourer, D. J., & Gofseyeff, M. (1967). Sequential effects in fixed-ratio postreinforcement pause duration. *Psychonomic Science, 9,* 387–388.

Neef, N. A., Marckel, J., Ferreri, S. J., Bicard, D. F., Endo, S., Aman, M. G., . . . Armstrong, N. (2005). Behavioral Assessment of Impulsivity: A comparison of children with and without Attention Deficit Hyperactivity Disorder. *Journal of Applied Behavior Analysis, 38*(1), 23–37.

O'Driscoll, G. A., Dépatie, L., Holahan, A. V., Savion-Lemieux, T., Barr, R. G., Jolicoeur, C., & Douglas, V. I. (2005). Executive functions and methylphenidate response in subtypes of Attention-Deficit/Hyperactivity Disorder. *Biological Psychiatry, 57*(11), 1452–1460.

Parry, P. A., & Douglas, V. I. (1983). Effects of reinforcement on concept identification in hyperactive children. *Journal of Abnormal Child Psychology, 11*(2), 327–340.

Pastor, P. N., & Reuben, C. A. (2008). Diagnosed Attention Deficit Hyperactivity Disorder and learning disability: United States, 2004–2006. *National Center for Health Statistics. Vital Health Stat, 10*(237).

Paule, M. G., Chelonis, J. J., Buffalo, E. A., Blake, D. J., & Casey, P. H. (1999). Operant test battery performance in children: Correlation with IQ. *Neurotoxicology and Teratology, 21*(3), 223–230.

Paule, M. G., Cranmer, J. M., Wilkins, J. D., Stern, H. P., & Hoffman, E. L. (1988). Quantitation of complex brain function in children: Preliminary evaluation using a nonhuman primate behavioral test battery, *Neurotoxicology, 9(3)* 367–378.

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

Pliszka, S. R., Greenhill, L. L., Crimson, M. L., Sedillo, A., Carlson, C., Conners, C. K., . . . Toprac, M. G. (2000). The Texas Children's Medication Algorithm Project: Report of the Texas Consensus Conference Panel on medication treatment of Childhood Attention-Deficit/Hyperactivity Disorder. Part I. *Journal of the American Academy of Child & Adolescent Psychiatry, 39*(7), 908–919.

Polanczyk, G., deLima, M. S., Horta, B. L., Biederman, J., & Rohde, L. A. (2007). The worldwide prevalence of ADHD: A systematic review and metaregression analysis. *American Journal of Psychiatry, 164*(6), 942–948.

Rapport, M. (1986). Hyperactivity and frustration: The influence of control over and size of rewards in delaying gratification. *Journal of Abnormal Child Psychology, 14*(2), 191–204.

Richardson, N. R., & Roberts, D. C. S. (1996). Progressive ratio schedules in drug self-administration studies in rats- a method to evaluate reinforcing efficacy. *Journal of Neuroscience Methods, 66*(1), 1–11.

Roane, H. S. (2008). On the applied use of progressive-ratio schedules of reinforcement. *Journal of Applied Behavior Analysis, 41*(2), 155–161.

Roberts, D. C. (1989). Breaking points on a progressive ratio schedule reinforced by intravenous apomorphine increase daily following 6-hydroxydopamine lesions of the nucleus accumbens. *Pharmacology, Biochemistry and Behavior, 32*(1), 43–47.

Salamone, J. D., Correa, M., Mingote, S. M., Weber, S. M., & Farrar, A. M. (2006). Nucleus accumbens dopamine and the forebrain circuitry involved in behavioral activation and effort-related decision making: Implications for understanding anergia and psychomotor slowing in depression. *Current Psychiatry Reviews, 2*(2), 267–280.

Schweitzer, J. B., & Sulzer-Azaroff, B. (1995). Self-control in boys with attention deficit hyperactivity disorder: Effects of added stimulation and time. *Journal of Child Psychology and Psychiatry, 36*(4), 671–686.

Shiels, K., Hawk, L. W., Reynolds, B., Mazzullo, R., Rhodes, J. J., Pelham, W. E., . . . Gangloff, B. P. (2009). Effects of methylphenidate on discounting of delayed rewards in Attention Deficit/Hyperactivity Disorder. *Experimental and Clinical Psychopharmacology, 17*(5), 291–301.

Skjoldager, P., Pierre, P., & Mittleman, G. (1993). Reinforcer magnitude and progressive ratio responding in the rat: Effects of increased effort, prefeeding, and extinction. *Learning and Motivation, 24*(3), 303–343.

Solanto, M. V., Abikoff, H., Sonuga-Barke, E., Schachar, R., Logan, G. D., Wigal, T., . . . Turkel, E. (2001). The ecological validity of delay aversion and response inhibition as measures of impulsivity in AD/HD: A Suppl. to the NIMH Multimodal Treatment Study of AD/HD. *Journal of Abnormal Child Psychology, 29*(3), 215–228.

Sonuga-Barke, E., Taylor, E., Sembi, S., & Smith, J. (1992). Hyperactivity and delay aversion: I. The effect of delay on choice. *Journal of Child Psychology and Psychiatry, 33*(2), 387–398.

Spencer, S. V., Hawk, L. W., Jr., Richards, J. B., Shiels, K., Pelham, W. E., Jr., & Waxmonsky, J. G. (2009). Stimulant treatment reduced lapses in attention among children on intra-individual response time distributions. *Journal of Abnormal Child Psychology, 37,* 805–816.

Tripp, G., & Alsop, B. (2001). Sensitivity to reward delay in children with attention deficit hyperactivity disorder (ADHD). *Journal of Child Psychology and Psychiatry, 42*(5), 691–698.

Tripp, G., & Wickens, J. R. (2008). Dopamine transfer deficit: A neurobiological theory of altered reinforcement mechanisms in ADHD. *Journal of Child Psychology and Psychiatry, 49*(7), 691–704.

Volkow, N. D., Fowler, J. S., Wang, G., Ding, Y., & Gatley, S. J. (2002). Role of dopamine in the therapeutic and reinforcing effects of methylphenidate in humans: Results from imaging studies. *European Neuropsychopharmacology, 12*(6), 557–566.

Volkow, N. D., Wang, G., Kollins, S. H., Wigal, T. L., Newcorn, J. H., Telang, F., . . . Swanson, J. M. (2009). Evaluating dopamine reward pathway in ADHD: Clinical implications. *JAMA: Journal of the American Medical Association, 302*(10), 1084–1091.

Wigal, T., Swanson, J. M., Regino, R., Lerner, M. A, Soliman, I., Steinhoff, K., . . . Wigal, S. B (1999). Stimulant medications for the treatment of ADHD: Efficacy and limitations. *Mental Retardation and Developmental Disabilities Research Reviews, 5*(3), 215–224.

Wilkison, P. C., Kircher, J. C., McMahon, W. M., & Sloane, H. N. (1995). Effects of methylphenidate on reward strength in boys with Attention-Deficit Hyperactivity Disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 34*(7), 897–901.

Wise, R. A. (2004). Dopamine, learning and motivation. *Nature Reviews Neuroscience, 5*(6), 483–494.

Received July 15, 2010
Revision received January 5, 2011
Accepted January 10, 2011 ■