

*EFFECTS OF METHYLPHENIDATE ON  
SENSITIVITY TO REINFORCEMENT IN  
CHILDREN DIAGNOSED WITH ATTENTION  
DEFICIT HYPERACTIVITY DISORDER:  
AN APPLICATION OF THE MATCHING LAW*

LAURA K. MURRAY

WESTERN MICHIGAN UNIVERSITY

AND

SCOTT H. KOLLINS

DUKE UNIVERSITY MEDICAL CENTER

The behavior of children diagnosed with attention deficit hyperactivity disorder (ADHD) has been hypothesized to be the result of decreased sensitivity to consequences compared to typical children. The present study examined sensitivity to reinforcement in 2 boys diagnosed with ADHD using the matching law to provide more precise and quantitative measurement of this construct. This experiment also evaluated the effects of methylphenidate (MPH) on sensitivity to reinforcement of children with ADHD. Subjects completed math problems to earn tokens under four different variable-interval (VI) schedules of reinforcement presented in random order under both medicated and nonmedicated conditions. Results showed that, in the medicated condition, the matching functions for both subjects resulted in higher asymptotic values, indicating an overall elevation of behavior rate under these conditions. The variance accounted for by the matching law was also higher under the medicated conditions, suggesting that their behavior more closely tracked the changing rates of reinforcement while taking MPH compared to placebo. Under medicated conditions, the reinforcing efficacy of response-contingent tokens decreased. Results are discussed with respect to quantifying behavioral changes and the extent to which the drug interacts with prevailing contingencies (i.e., schedule values) to influence behavioral variability.

DESCRIPTORS: attention deficit hyperactivity disorder, methylphenidate, sensitivity to reinforcement, matching law

---

Attention deficit hyperactivity disorder (ADHD) is one of the most commonly di-

---

This work was completed in partial fulfillment of the requirements for the MA degree in the Department of Psychology at Western Michigan University. Portions of this work were presented at the annual meeting of the Association for the Advancement of Behavior Therapy (Washington, D.C., November, 1998) and at the annual meeting of the Association for Behavior Analysis (Chicago, May, 1999). We thank the following people, without whose help the project would not have been possible: Wayne Fuqua, Alan Poling, Tom Critchfield, Scott Musial, and the families who participated in the project.

Correspondence regarding this article should be directed to Scott H. Kollins, Department of Psychiatry, Duke University Medical Center, Box 3431, Durham, North Carolina 27710.

agnosed behavior disorders among preadolescent children in the United States (American Psychiatric Association, 1994; Barkley, 1997), and questions regarding its etiology, symptom variation, and course have generated a vast literature. In efforts to understand ADHD, researchers have attempted to explain the behavioral symptoms using various theoretical models.

Barkley (1990, 1997) offers a comprehensive theoretical account of ADHD behavior that implicates the construct of behavioral inhibition as the major impairment associated with observed behavioral problems. This model suggests that a behavioral inhibition system controls how children consider

the potential outcome of their ongoing behavior; in children with ADHD, this system provides inadequate opportunities to regulate their behavior.

Another approach to conceptualizing ADHD behavior that relies less on the construct of behavioral inhibition proposes that the behavior of children with ADHD does not change following certain consequences in the same manner as the behavior of typical children (Douglas, 1983; Haenlein & Caul, 1987). Such theories predict that, to maintain similar levels of behavior, children with ADHD require higher rates of reinforcement than do normal children (Haenlein & Caul, 1987). These models also predict that the behavior of children with ADHD will not change or adjust as readily as the behavior of typical peers under conditions in which environmental contingencies are changing. This differential pattern of responding to consequences has been described as sensitivity to reinforcement.

A number of studies have investigated the construct of sensitivity to reinforcement in children with ADHD across various tasks and settings, producing mixed results (e.g., Cunningham & Knights, 1978; Douglas & Parry, 1983; Haenlein & Caul, 1987; Parry & Douglas, 1983). For example, in studies examining the behavior of children with ADHD under continuous reinforcement and partial reinforcement schedules, some reported no differences in the behavior of children with ADHD and typical peers (Cunningham & Knights, 1978; Pelham, Milich, & Walker, 1986), whereas others reported that the behavior of children with ADHD was less efficient (i.e., they earned fewer reinforcers) than the behavior of their normal peers with respect to overall points earned (Douglas & Parry, 1983; Parry & Douglas, 1983). The interpretation of these studies from a functional analytic perspective is difficult, given the lack of clear specification of both response units and the contin-

gent relation between the responses and consequences across the studies. Further, the use of different experimental preparations, varying subject characteristics, and different measurement strategies are likely reasons for the inconclusive results reported across these studies.

Due to the mixed results and discrepant methods used to measure sensitivity to reinforcement, some researchers have developed methods for studying these processes in ADHD children that are more standardized and are derived from experimental work with nonhumans. For example, the deficits associated with ADHD have been described as being associated with differences in instrumental behavioral variability (e.g., Saldana & Neuringer, 1998) and as relating to differences in the extent to which reinforcement influences subsequent behavior (e.g., Sagvolden, Aase, Zeiner, & Berger, 1998). Another standardized, quantitative approach for studying the basic behavioral processes associated with ADHD is matching theory, which provides a quantitative account of how the behavior of an organism changes in response to changing environmental conditions and has been used theoretically to describe sensitivity to reinforcement (Baum, 1979; Herrnstein, 1961, 1970). Herrnstein initially described the manner in which behavior maintained by variable-interval (VI) schedules varies as a negatively accelerating hyperbolic function of obtained reinforcement rates. This mathematical account of behavior specifies the relationship between reinforcement rate and behavior rate as follows (Herrnstein, 1970):

$$R = \frac{kr}{r + r_0}. \quad (1)$$

In this equation,  $R$  is the rate of the target response,  $r$  is the rate of reinforcement contingent upon the target response,  $k$  is a free parameter interpreted as the asymptotic response rate, and  $r_0$  is a free parameter that

theoretically represents the rate of all other reinforcement delivered to the subject exclusive of the target response. Quantitatively,  $r_0$  represents the reinforcement rate required to maintain half-maximal ( $k/2$ ) responding and has been conceptualized as a measure of reinforcer efficacy (e.g., Herrnstein, 1970; Heyman, 1992).

Research has demonstrated the value of Equation 1 and its derivatives as valid descriptors of behavior with both nonhumans (see Baum, 1979, and Davison & McCarthy, 1988, for reviews) and humans (see Kollins, Newland, & Critchfield, 1997, and Pierce & Epling, 1983, for reviews). Further, the matching law has been shown to be useful in describing clinically meaningful behavior in humans (e.g., Bradshaw, Szabadi, & Bevan, 1976; Mace, McCurdy, & Quigley, 1990; Mace, Neef, Shade, & Mauro, 1994; Martens & Houk, 1989; McDowell, 1982).

At least one published study has used matching theory to assess sensitivity to reinforcement in children with ADHD. In this study, Kollins, Lane, and Shapiro (1997) examined the differences in sensitivity to reinforcement between children with ADHD and normal children by describing their behavior under concurrent VI VI schedules with a derived linear equation based on Equation 1 (Baum, 1979). Results demonstrated that, compared to normal children, the behavior of children with ADHD was less likely to change in conjunction with changes in the rates of reinforcement, as evidenced by lower slope values from the generalized matching equation. These findings support the hypothesis that the behavior of children with ADHD does not change in adaptive ways when environmental conditions change (i.e., lower sensitivity to reinforcement; Barkley, 1991, 1997; Haenlein & Caul, 1987; Quay, 1997). The results of Kollins, Lane, and Shapiro (1997) also add to an accumulating literature supporting the

matching law as an accurate mathematical description of human choice in applied settings. The Kollins, Lane, and Shapiro study, however, examined children only under unmedicated conditions. Given the frequency with which stimulant medication is used in the treatment of ADHD (e.g., Pelham, 1993), it would be useful to determine whether matching theory can account for the behavioral changes seen in children on and off medication.

The present study had two primary goals. First, we sought to determine if matching theory described the behavior of children diagnosed with ADHD under different VI schedules, thus replicating the work of Kollins, Lane, and Shapiro (1997). We chose to examine the behavior of children with ADHD using the single-alternative matching equation (Equation 1) instead of the concurrent procedure used by Kollins, Lane, and Shapiro, because it allows a more straightforward interpretation of how behavior is influenced by changing contingencies. Specifically, the single-alternative matching equation describes how the rate of a single response changes when contingencies for that response change. This stands in contrast to the concurrent procedure, which calculates sensitivity to reinforcement on the basis of relative changes in two or more responses as a result of relative changes in two or more reinforcement rates. Our second goal was to determine whether matching theory could be used to quantitatively describe the effects of a commonly used medication, methylphenidate (MPH), on the behavior of children with ADHD. Specifically, we sought to determine whether MPH exerts its clinical effects by altering sensitivity to reinforcement in children with ADHD.

## METHOD

### *Participants and Setting*

Participants were 2 boys, ages 7 and 10, recruited from the local community via post-

ed flyers and word of mouth, who had previously been diagnosed with ADHD based on the *Diagnostic and Statistical Manual of Mental Disorders* (4th ed., APA, 1994). Both participants also received a T score greater than 65 on the Attentional Problems subscale of the Child Behavior Checklist (Achenbach & Edelbrock, 1991) as rated by two adults with whom each child had significant contact and a T score greater than 65 on the Impulsive-Hyperactive subscale of the Conners Parent Rating Scale-48 (Conners, 1990).

The first subject, Derrek, was a 10-year-old boy in fifth grade who was prescribed 10 mg of MPH twice a day. The other subject, Willis, was a 7-year-old boy in second grade who was also prescribed 10 mg of MPH twice a day. No other medications were prescribed while they participated in the study. This study was conducted in a laboratory setting at Western Michigan University, which included one playroom filled with toys and rewards and a larger room where the volunteers participated in the experimental procedures. The experimental room had a large conference table in the middle where the children worked on math problems, a wall of desks containing a computer and printer, and a wall of bookshelves. Children and their parents consented to the experiment with the knowledge that it was not designed to provide direct clinical services (i.e., assessment or treatment) for the children, and most sessions were conducted on weekends. This study was approved by the Human Subjects Institutional Review Board at Western Michigan University.

#### *Apparatus and Materials*

*Reinforcer survey.* A reinforcer survey (based on that of Northup, Fusilier, Swanson, Roane, & Borrero, 1997) containing 42 common childhood reinforcers was read to each participant during the screening sessions. Children rated each item on the sur-

vey as *like not at all*, *like a little*, or *like a lot*. Responses from the survey can be classified into six general categories including edible items, peers, activities, tangible items, teacher attention, and escape. Children were also asked to list other small toys, edibles, or activities they enjoyed but that were not on the survey. The most highly rated items were made available for each child during experimental sessions and were assigned token "prices" based on the monetary cost of the item or on the rated preference for the activity or attention. A daily record was kept of which items each individual chose during the experimental sessions.

*Math sheets.* The target response for the study was the completion of easy math problems (irrespective of accuracy) that were presented on paper in five rows of five problems each, for a total of 25 problems per sheet. The completion of these math problems was selected as a potentially externally relevant response that could be performed at a relatively high rate. Easy math problems were defined as those that could be completed with greater than 90% accuracy during repeated trials in the screening sessions, resulting in baseline rates of 23.1 problems per minute and 11.9 problems per minute for Derrek and Willis, respectively. We did not specify a priori a criterion response rate for the problems, but concluded that the rates were sufficiently high to come in contact with the contingencies for the richest schedules selected (e.g., VI 6 s). The difficulty level of the problems was individually determined. Willis was given problems consisting of two numbers, such as 7 and 2, and was instructed to circle the larger of the two numbers. Derrek was given single-digit addition problems, such as  $7 + 2$ , to complete. Colored paper was used for the math sheets (blue, green, pink, and yellow), and each color corresponded to a different VI schedule value throughout the experiment (see Procedure below). Total number of com-

pleted problems and accuracy for baseline (and all other sessions) are reported in Appendixes A and B for Derrek and Willis, respectively.

*Tokens and back-up reinforcers.* Poker chips were used as tokens, with each chip representing 1 point. Preferred reinforcers (based on the self-report survey) were assigned different point values based on their monetary worth (for toys) or their rated preference (for activities). Each child had the option to save or spend his tokens following each experimental trial, and tokens could be used for a single reward or for multiple rewards. Children were allowed to keep all items they selected as back-up reinforcers. The token costs of some of the more expensive items were such that repeated trials were necessary to accumulate the required amounts. Children were allowed to carry over tokens from one experimental session to the next.

*Cuing tape.* Audiocassette tapes presented a series of tones programmed to sound according to different VI schedules. The schedule values were approximated based on a Poisson distribution (Fleshler & Hoffman, 1962) and consisted of 12 intervals with the following means: 6, 12, 20, 30, and 60 s. Once the tapes were made, they were checked to ensure that average reinforcement rates for each schedule value were accurate. The order of VI schedule presentation was randomized for each session. The researcher listened to the tapes through earplug headphones and delivered tokens following the first completed response after a tone. The primary researcher practiced listening to the schedule tapes and delivering tokens with a colleague before participants were run through sessions.

*Medication procedure.* Both children received either their standard dose of MPH (10 mg) or a placebo capsule on each day of the study. We chose to use the standard clinical doses of MPH to increase external validity. Medications were prepared by a phar-

macist from the university health center according to a standardized procedure. MPH tablets (10 mg) were encapsulated in opaque capsules to conceal taste, odor, and color. The capsules were then filled with dextrose. Placebo capsules were identical in appearance, but contained only dextrose. The pharmacist was given a pseudorandom sequence of how the MPH and placebo pills were to be prepared (with the rule of never exceeding 2 days in a row of either MPH or placebo). The pharmacist placed the appropriate capsules in a pill box labeled with Days 1 through 8. Prior to each session, the researcher telephoned the parents as a prompt to administer the capsule corresponding to the appropriate day and time agreed upon by the researcher and parents. All pills were administered 45 min prior to a scheduled session. To our knowledge, these procedures were adhered to in all cases. The experimenter, the child, and his parents were all blind to the medication status, with only the pharmacist and the senior investigator aware of the sequencing. Once the participant completed all sessions, the researcher opened a sealed envelope containing the medication and placebo sequence, breaking the double blind condition.

#### *General Procedure*

All efforts were made to hold sessions at approximately the same time each day. There were two screening sessions performed before baseline. The purpose of these screening sessions was threefold: (a) to administer the reinforcer survey to the children while they were on and off medication, because MPH has been shown to influence preference in children with ADHD (Northup et al., 1997); (b) to obtain a mean rate of problems completed under both medication and placebo conditions; and (c) to determine if the math problems chosen for the children were easy enough to maintain a mean accuracy of 90%.

*First screening session.* At the first session, the purpose and procedure of the study were reviewed with the parent and child and consent was obtained from each. The checklist, rating scale, and a release to contact the child's physician were completed by the parent. All sessions were conducted separately for both subjects. During the first session, it was determined that Derrek had taken his regular dosage of MPH less than 3 hr before the session, and his medication was thus considered active.<sup>1</sup> During Willis's first session, it was determined that he had taken his dosage of MPH more than 3 hr before the session, and his medication was considered inactive. Each participant then responded to the reinforcer survey and subsequently chose a reward such as an activity, edible item, or small toy. Next, the child completed three 10-min trials of math sheets. Each trial was separated by a 10-min break, during which a reward was chosen. Math sheets were scored to ensure that the child was completing the problems at 90% or better accuracy.

After the session, each child's prescribing physician was contacted and agreed to the child's participation in the study by providing written consent and a prescription to prepare the MPH and placebo capsules as described above.

*Second screening session.* Each child participated in procedures identical to the first screening session, except for medication status. For this second screening, Derrek had taken his medication more than 3 hr before the session; thus, his MPH was considered inactive. Willis had received his dosage of MPH less than 3 hr before the session, and

<sup>1</sup> Three hours was chosen because the elimination half-life for methylphenidate is between 2 and 3 hr (Julien, 1998). Further, peak behavioral effects are typically seen between 1.5 and 2 hr after administration. Thus, we reasoned that behavioral effects of the drug would be observed 1.5 to 3 hr after administration, after which time at least half of the drug would have been metabolized.

his medication was considered active. No differences were found between the types of reinforcers that Derrek and Willis selected during these first two screening sessions.

*Baseline.* Following the screening sessions, each child participated in two separate sessions without receiving any capsules. The purpose of these sessions was to obtain baseline data during the experimental task without the effects of taking any capsules (either placebo or MPH). These sessions were conducted either on weekends when the children had not taken any medication that day or in the afternoons of school days when it had been at least 3 to 4 hr since medication was taken. The child reported to the laboratory and was seated with math worksheets directly in front of him and a plastic jar placed further in front of him to hold the tokens. Each child was given the following instructions prior to beginning the task (adapted from Northup et al., 1997):

Once I say "START," you can earn tokens for doing these math problems. You can work as fast as you want or as slow as you want. You can do as much as you want, as little as you want, or none at all. Sometimes when you are working, I will drop a token in this jar. I will say "STOP" when we can take a break. Your break will be for 10 minutes and during that time, you may cash in the tokens you receive for prizes that you said you liked. After 10 minutes, we will work again for a while.

When the experimenter said "start," she started the cue tape and the child began the math problems. A token was dropped into the jar every time the child completed a math problem following the completion of an interval. The rates of reinforcement varied based on the different VI schedules. For example, the VI-6 s schedule produced a tone, on average, every 6 s, producing approximately 10 tokens per minute. Follow-

ing 10 min on one schedule, the experimenter said "stop" and the child was allowed a 10-min break, during which he could cash in his tokens for a variety of reinforcers based on his self-reported preferences, or he could save his tokens.

During each session, the completion of math problems was reinforced according to four different VI schedules presented in random order. A discriminative stimulus (different colors of paper for the math sheets) accompanied each different VI schedule. Derrek participated under the following schedules in random order: VI 6 s, VI 12 s, VI 20 s, and VI 30 s. In an effort to generate greater response variability, Willis participated under the following schedules in random order: VI 6 s, VI 12 s, VI 30 s and VI 60 s. Appendixes A and B report the exact sequences of VI schedule presentation for Derrek and Willis, respectively.

*Phase 2.* Following these baseline measures, the volunteers participated in eight more sessions consisting of the medication manipulation between MPH and placebo. Forty-five minutes prior to each scheduled session, the researcher telephoned and the parents of the child were prompted to administer the pill from the appropriate day in their pill box. The child then completed the procedures in an identical manner as during baseline. Each participant completed 4 days under MPH conditions and 4 days under placebo conditions. Dependent variables for baseline and Phase 2 sessions included the number of problems completed, percentage accuracy, number of tokens received, and rewards chosen after each 10-min session.

#### *Data Analysis*

Completed problems were summed under each schedule condition for each experimental day. The total number of completed problems was counted on more than one occasion by the first author to ensure reliability of the primary dependent variable. In addition,

an independent researcher rescored 60% of the sessions for both participants, resulting in a 100% interrater reliability for the number of problems completed. Based on previous matching research with human participants using single VI schedules, data were aggregated across sessions and means and standard deviations of response rates (in completed math problems per minute) were calculated at each schedule value (e.g., Bradshaw et al., 1976). These data were then expressed as a function of the obtained rate of reinforcement at each schedule value (in tokens per minute). Rectangular hyperbole (Equation 1) were fit to the data by computer program (Table Curve 2D, V.4, SPSS, Inc.) using nonlinear least squares regression analysis (Wilkinson, 1961), giving estimates of the theoretical maximum response rate ( $k$ ) and the reinforcement frequency corresponding to half-maximal response rate ( $r_0$ ). Proportion of variance in the data ( $r^2$ ) accounted for by the hyperbolic function was also calculated.

## RESULTS

Figures 1 and 2 illustrate response rates and standard deviations for Derrek and Willis, respectively. Because there were no differences between the baseline and placebo conditions, these were combined and are reported together. For Derrek, MPH produced clear increases in response rate across all schedule conditions. This difference was substantiated by a paired two-sample  $t$  test ( $t = -20.6$ ;  $df = 3$ ;  $p < .001$ ). MPH did not have general effects on response variability as measured by standard deviation for Derrek ( $t = 0.38$ ;  $df = 3$ ;  $p = .73$ ). For Willis, MPH did not have overall rate-changing effects on math problem completion, although there was a tendency for MPH to *reduce* placebo and baseline rates of problem completion ( $t = 2.0$ ;  $df = 3$ ;  $p = .07$ ). MPH also decreased response variabil-

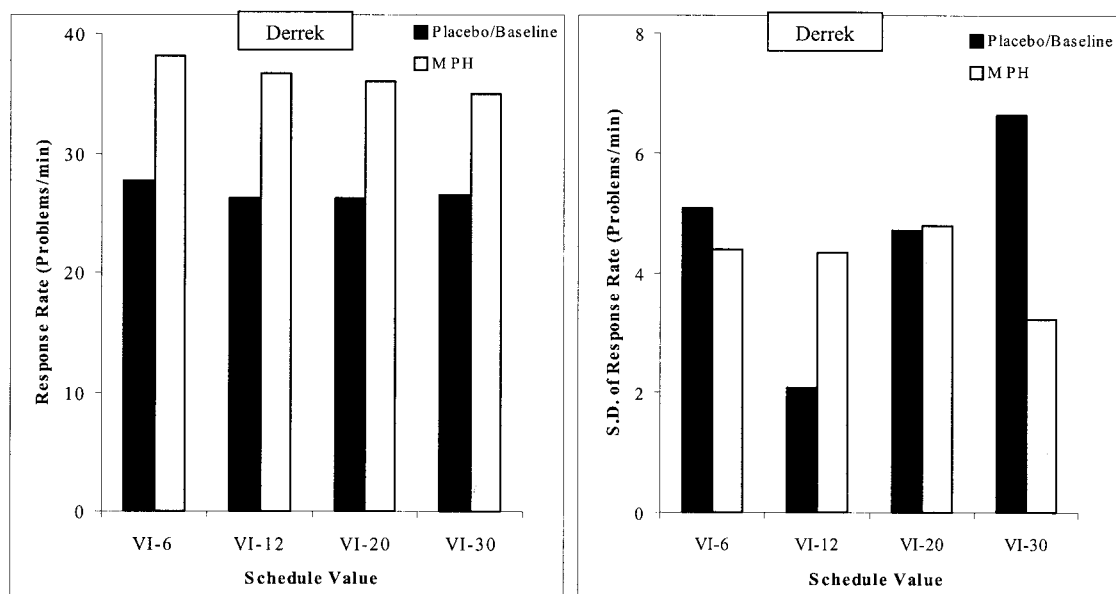


Figure 1. Mean response rates and standard deviations (*SD*) across schedule values for Derrek.

ity for Willis, as evidenced by smaller standard deviations of response rate ( $t = 1.74$ ;  $df = 3$ ;  $p = .09$ ). There were no significant differences for response accuracy for either Derrek or Willis across MPH and placebo conditions, although there was a tendency for placebo to *increase* response accuracy for Willis ( $t = 2.29$ ;  $df = 3$ ;  $p = .11$ ). It should be noted that accuracy rates for both participants were very high across both conditions (Willis: 94.0% for placebo, 92.3% for MPH; Derrek: 99.1% for placebo, 99.1% for MPH).

#### *Matching Performance: Baseline*

Under baseline conditions, Derrek and Willis completed 231.1 and 119.0 problems per session respectively across days, yielding mean rates of 39.8 and 28.6 reinforcers per session. Appendixes A and B report data under each schedule value across both baseline days.

With respect to sensitivity to changing contingencies under baseline conditions, matching analysis yielded parameter estimates for Derrek of 23.93 responses per

minute and 0.12 reinforcers per minute for  $k$  and  $r_0$ , respectively (data not shown). Equation 1 accounted for 5% of the variance in Derrek's responding across VI conditions in baseline. For Willis, Equation 1 accounted for 10% of the variance in responding and yielded parameter estimates of 11.59 responses per minute and  $-0.05$  reinforcers per minute, respectively, for  $k$  and  $r_0$ .

#### *Matching Performance: Placebo and MPH Conditions*

Two of the principal goals of the present study were (a) to determine if matching theory described the behavior of children with ADHD under different VI schedules and (b) to use matching theory as a tool to assess whether MPH alters sensitivity to reinforcement in children with ADHD. To address these goals, Figures 3 and 4 show the rate of completed math problems by obtained reinforcement rate for each child under MPH and placebo conditions, including the fitted hyperbolic functions and the estimated equation parameters.

Figure 3 demonstrates that the matching

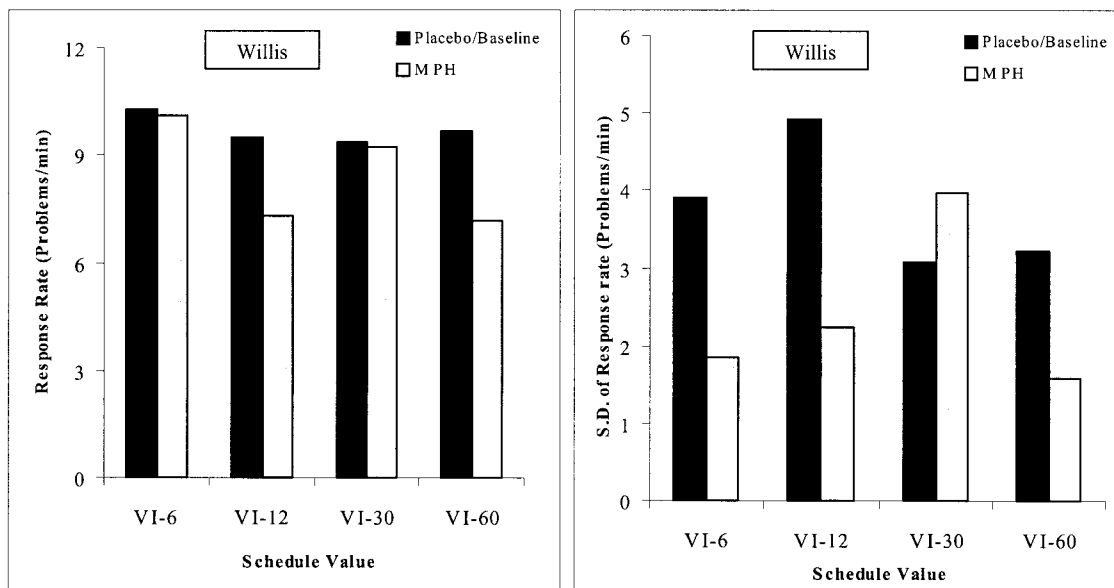


Figure 2. Mean response rates and standard deviations (*SD*) across schedule values for Willis.

law accounted for 8.25% and 96% of the variance under placebo and MPH conditions, respectively, for Derrek. Thus, matching theory adequately described the relationship between the rate of problems completed and contingent reinforcement under the MPH condition. Under placebo conditions, the hyperbolic function reached asymptote at 29.44 responses per minute with an  $r_0$  value of 0.13 reinforcers per minute. During MPH conditions, the function reached a higher asymptote of 39.37 responses per minute and a higher value of  $r_0$  (0.30 reinforcers per minute). These parameters demonstrate a higher mean maximum response rate under the MPH condition. The estimated value of  $r_0$  was also higher under MPH conditions, suggesting that more reinforcers were needed to maintain half-maximal responding.

Figure 4 displays Willis's data, showing that 17% and 43% of the variance was accounted for by the matching equation under the placebo and MPH conditions, respectively. Thus, matching theory better described behavioral change under MPH ver-

sus placebo conditions for Willis. The placebo conditions resulted in matching law parameters of 9.20 responses per minute ( $k$ ) for the asymptote and 0.13 reinforcers per minute for  $r_0$ . Under MPH conditions, Equation 1 yielded a slightly higher asymptotic value of 10.14 responses per minute and an estimated  $r_0$  value of 0.396 reinforcers per minute. Willis's responding reached slightly higher maximum response rates under MPH conditions, although this difference may be due to response variability unrelated to the MPH. The estimated values of  $r_0$  demonstrate that Willis also required more reinforcers per minute to maintain half-maximal responding under MPH conditions than under placebo conditions.

## DISCUSSION

The first goal of this study was to evaluate whether Herrnstein's (1970) matching equation could adequately describe the behavior of children diagnosed with ADHD under changing VI schedules of reinforcement. Results suggest that this equation described the

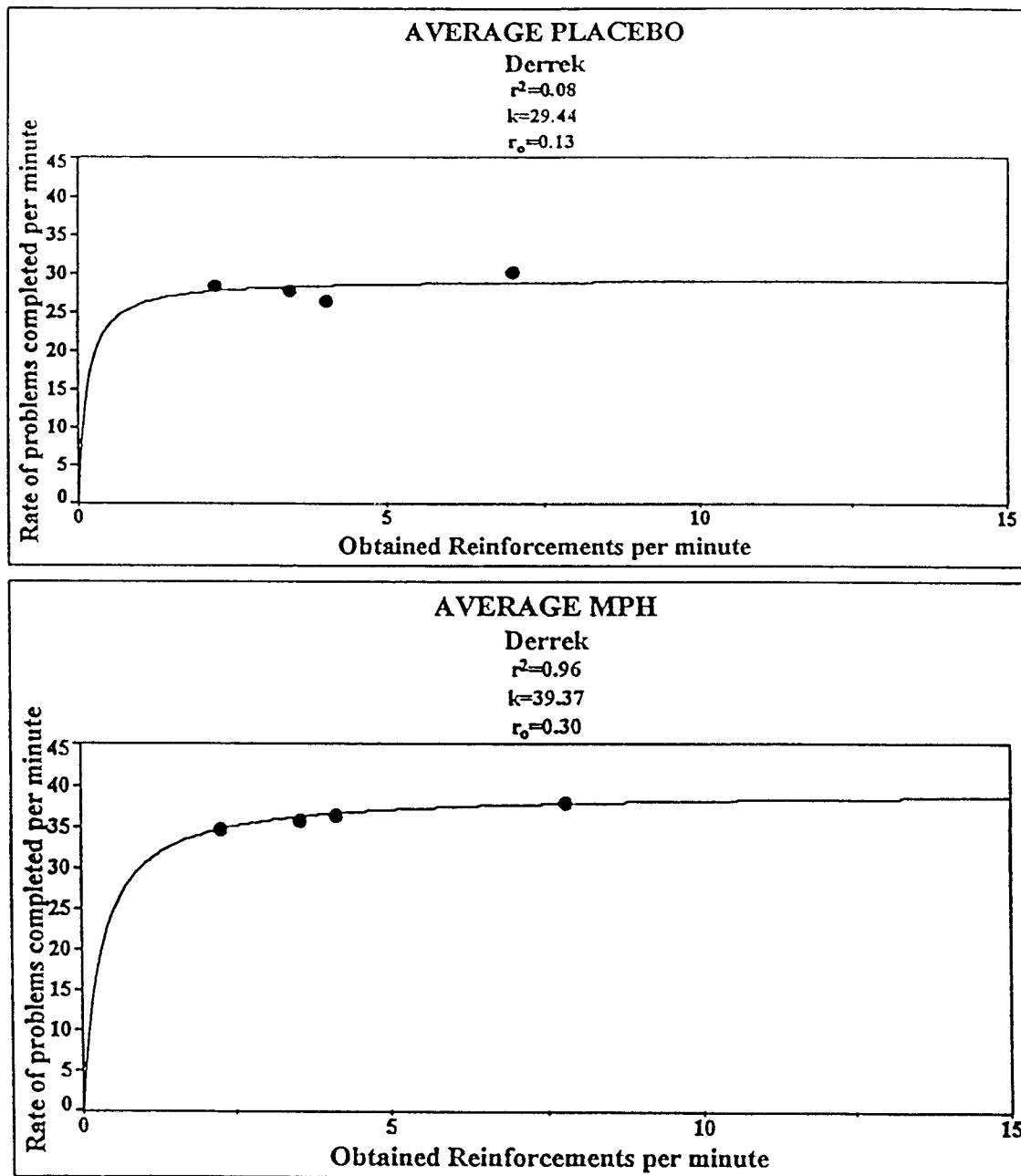


Figure 3. Mean rates of responding (problems per minute) by mean obtained reinforcers per minute for Derrek under MPH and placebo.

relationship between behavior and contingent reinforcement under the MPH condition for Derrek only. The second goal of the study was to determine whether the matching equation could be used to quantify

changes in behavior following administration of MPH. As shown in Figures 1 and 2, the matching equation accounted for only a minimal amount of variance in the behavior of both participants under placebo condi-

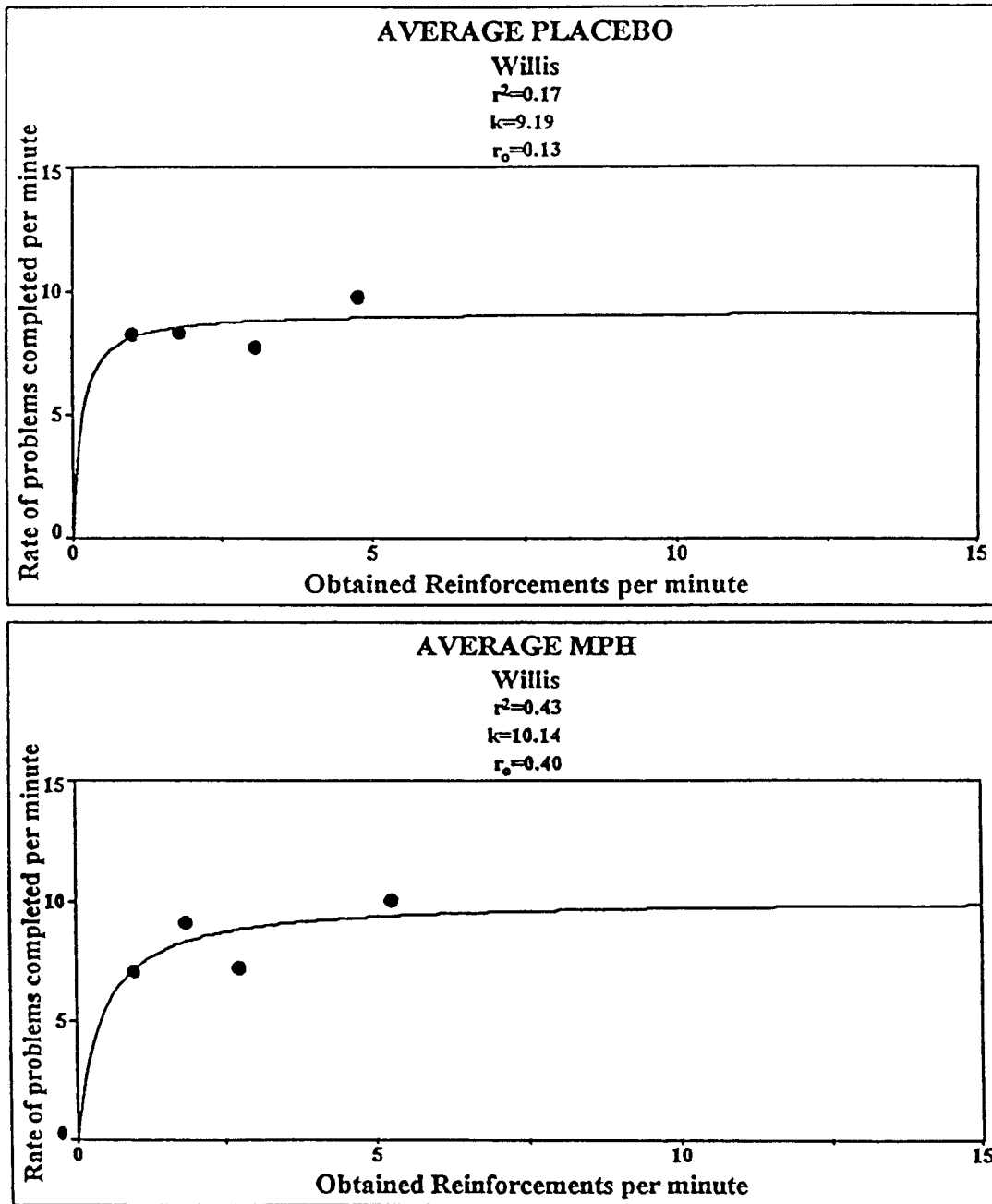


Figure 4. Mean rates of responding (problems per minute) by mean obtained reinforcers per minute for Willis under MPH and placebo.

tions and described behavior better for both subjects during the MPH condition.

The matching functions for both subjects resulted in higher asymptotic values ( $k$ ) under MPH conditions, indicating that their

overall rates of behavior were elevated under these conditions compared to placebo conditions. At least two interpretations are possible: The parameters may have simply reflected the rate-increasing effects of MPH

(e.g., Barkley, 1990; Heyman, 1992; Rapport, DuPaul, & Smith, 1985), or the increase in  $k$  may have reflected a tendency for greater overall on-task behavior (e.g., Barkley, 1990; Barkley & Cunningham, 1979), which would further support research on the effectiveness of MPH to increase on-task behavior (for review, see Barkley, 1990). One potential way to investigate which of these two possibilities was functioning would be to systematically manipulate the  $k$  value while holding other variables constant. Research with nonhumans has demonstrated that these two parameters are independent and that increasing response requirements (such as the force required to press a lever) can result in changed  $k$  values while  $r_o$  remains constant (e.g., Heyman & Monaghan, 1987). An analogous manipulation of the present preparation might involve systematically changing the difficulty level of the math problems. If MPH exerted effects only on reinforcement efficacy independently of response rates, we would expect a change in  $k$  under such conditions while  $r_o$  remained constant.

A second finding of the present study was that the variance accounted for by the matching law was higher under the MPH conditions for both subjects, suggesting that their behavior more closely tracked the changing rates of reinforcement while taking MPH versus placebo. The matching equation, however, failed to account for more than a modest proportion of variance in three of four experimental conditions (2 participants under medication and placebo conditions). A number of testable hypotheses may help to clarify why this was the case. For example, the children's responding may have not come under the control of the discriminative stimuli (color of paper) associated with the different schedule values. Also, the children may have not been exposed to the schedule values long enough to observe steady-state behavior. Alternatively, the in-

structions used for the task may not have controlled behavior in the expected manner. All of these possibilities could be evaluated not only to determine the extent to which the behavior of children with ADHD tracks contingencies, but how their behavior differs from that of typical peers.

Contrary to our initial hypothesis, however, the values of  $r_o$  increased under MPH conditions compared to placebo conditions. This finding suggests that although the behavior of participants tracked changing contingencies more closely under MPH conditions (based on higher  $r^2$  values), the reinforcing efficacy of response-contingent tokens decreased under MPH conditions. One potential reason we may have observed increases in  $r_o$  under MPH conditions is that we also observed increases in  $k$ . As such, the interpretation becomes somewhat difficult. For example, in Derrek's case, 0.13 reinforcers per minute maintained approximately 14.5 responses per minute (half-maximal) under placebo conditions. Under MPH, 0.3 reinforcers per minute maintained approximately 19.5 responses per minute. Unless  $k$  can be held constant, it is difficult to determine precisely the extent to which MPH altered  $r_o$  independent of changes in asymptotic response rate. This finding warrants future investigation, especially to determine the extent to which MPH actually alters reinforcer efficacy.

Another approach to conceptualizing the behavioral mechanism of action in ADHD children might be to evaluate the extent to which the drug interacts with prevailing contingencies (i.e., schedule values) to influence behavioral variability. Our results suggest that MPH had the effect of reducing response variability (measured by standard deviations of response rates) under certain schedule conditions. This finding is consistent with the hypothesis that a core deficit in children with ADHD is increased behavioral variability (e.g., Saldana & Neuringer,

1998). In any case, conceptualizing MPH effects in terms of how the drug influences dimensions of ongoing behavior should lead behavior analysts to a better understanding of how MPH exerts clinically meaningful effects.

This study represents an attempt to further explain the behavior seen in children with ADHD by extending basic science principles to applied settings of human behavior. Specifically, the present research used VI schedules and matching theory to examine the underlying behavioral mechanisms associated with ADHD under different environmental contingencies, and after taking MPH versus a placebo. Results suggest that MPH may exert its effect by altering basic behavioral mechanisms associated with sensitivity to changing contingencies. Other experimental preparations may be useful to further clarify the behavioral mechanisms associated with MPH's effectiveness. As mentioned previously, Kollins, Lane, and Shapiro (1997) used a concurrent-schedules procedure to evaluate the extent to which the behavior of children with ADHD changed in relation to changing contingencies. The findings suggested relative insensitivity to changing consequences, as interpreted by the slopes of the obtained regression lines compared to typical participants. Such a preparation may be used in a within-subject design to assess slope values before and after MPH administration in children with ADHD.

Others have suggested that the behavior of children with ADHD may be characterized in a self-control/impulsivity framework (e.g., Barkley, 1997). Such a framework allows a variety of experimental preparations to examine the effects of MPH. For example, one study suggested that the choices of immediate versus delayed reinforcers may help to characterize the behavior of emotionally disturbed individuals and that such choice patterns may then be used to assess

the effects of different interventions (e.g., Neef, Shade, & Miller, 1994). A similar approach may be used with children with ADHD on and off medication to examine how the drug functions to reduce the probability of choices for immediate but smaller reinforcers.

Several aspects of the current study should be addressed in future research, including the manner in which schedule values are selected and presented and issues pertaining to external validity and generalizability. In comparison to other studies in the basic and applied areas, the VI schedules used in the present study were relatively rich and produced low response variation. Also, exposure to the schedules was relatively brief (10 min). These factors may have artificially limited response variation when contingencies changed across trials. In general, to the extent that researchers can overcome procedural challenges presented by this particular clinical population, future studies should attempt to utilize both a wider range of schedule values and longer session lengths to obtain optimal response variation under varying contingencies. There was also a tendency for participants to demonstrate the highest rate of responding during the first trial of each experimental session, regardless of schedule value (see Appendixes A and B). Because there was variation in rate (both increased and decreased rate of problems completed) as a function of schedule value in subsequent trials, it was difficult to determine whether this pattern of responding was the result of fatigue. Nevertheless, it may be prudent for future research in the area to implement a warm-up period at the beginning of sessions, in which subjects complete a trial under a single, relatively rich schedule to control for the potential effects of fatigue.

Several other methodological features of the present study may have limited the external validity and generalizability of the findings and should be addressed in subse-

quent research. For example, we used a very small sample size (2 participants), and medication administration was not directly monitored. Future studies should, if feasible, seek to extend these findings to more individuals diagnosed with ADHD and use direct administration of medication by research staff members to confirm compliance with experimental procedures and maximize the likelihood of standardization across conditions.

Another methodological limitation of the present study was that reinforcers were selected based on the subject's verbal report and were not functionally determined. Research has demonstrated that a paired-stimulus format of reinforcer preference assessment is the most accurate method for functionally determining salient reinforcers (e.g., DeLeon & Iwata, 1996; Northup, Jones, Broussard, & George, 1995). Thus, there may be a discrepancy between those reinforcers reported as preferred by the participants and those that would function as such after a more elaborate behavioral analysis.

The present findings should also be interpreted in light of two other more substantive issues pertaining to the external validity and generalizability of the results. First, the extent to which firm conclusions can be drawn regarding the relation between the independent variable and the dependent variable could be improved by addressing idiosyncrasies in the experimental procedure. Specifically, the use of experimenter-administered conditioned consequences and direct observation of the participants, among other factors, may have influenced the behavior of the children. Future research would be well served to take advantage of more efficient means of data collection and schedule presentation (i.e., use of computerized protocols, etc.). It has been argued that the use of more sophisticated, computer-based simulations enhances the realism of laboratory-based experimental procedures, and consequently, the external validity and generaliz-

ability of the research (e.g., DiFonzo, Hantula, & Bordia, 1998). It is important to note, however, that procedures similar to the ones used in the present experiment have been successfully used to characterize other clinically meaningful behavior. For example, Bradshaw et al. (1976) demonstrated that the single-rate matching equation described button-pressing behavior of an individual diagnosed with manic depression.

Second, we selected our primary response on the basis of whether the child would be familiar with it, and whether it could be emitted at a high rate. As a result, we saw little variation in response accuracy on the math problems, thus limiting the external validity of the study. An alternative way of assessing the behavioral mechanism of MPH might be to select responses that naturally occur in a child's environment and examine how the rate of these responses changes as environmental contingencies change. This naturalistic approach to studying the single-rate form of matching has been used before with children. For example, Martens, Lochner, and Kelly (1992) demonstrated that the hyperbolic form of the matching equation described the relation between academic engagement and teacher attention very well (variance accounted for: 99.1% and 87.6% for the 2 participants). This finding is also consistent with the finding that matching is a better descriptor of human behavior when more naturalistic responses are measured (Kollins, Newland, & Critchfield, 1997).

In spite of these limitations, we hope this work will be viewed as a heuristic to formulate questions regarding how drugs enter into relations with other environmental events to influence behavior change in children. Such questions may help further stimulate the field of applied behavioral pharmacology.

On a general level, our results support the application of principles derived from basic research to more applied settings. Such an

approach has been advocated repeatedly by applied behavior analysts (e.g., Mace, 1994; Mace & Wacker, 1994). There is an increasing body of literature specifically using mathematical accounts of behavior, such as the matching law, in applied settings with success (e.g., Kollins, Lane, & Shapiro, 1997; Mace et al., 1988; Martens, Halperin, Rummel, & Kilpatrick, 1990). Given the complex and dynamic nature of human behavior, the extent to which basic research principles can be used in applied settings has been debated (e.g., Fuqua, 1984). However, the progress basic research has made in understanding fundamental behavioral processes has been, and should continue to be, the source of many applied research ideas and methodologies.

## REFERENCES

- Achenbach, T. M., & Edelbrock, C. S. (1991). *Child behavior checklist and youth self-report*. Burlington, VT: Author.
- American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: Author.
- Barkley, R. A. (1990). *Attention deficit hyperactivity disorder: A handbook for diagnosis and treatment*. New York: Guilford Press.
- Barkley, R. A. (1991). The ecological validity of laboratory and analogue assessments of ADHD symptoms. *Journal of Abnormal Child Psychology*, *19*, 149–178.
- Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*, 65–94.
- Barkley, R. A., & Cunningham, C. E. (1979). Stimulant drugs and activity level in hyperactive children. *American Journal of Orthopsychiatry*, *49*, 491–499.
- Baum, W. M. (1979). Matching, undermatching, and overmatching in studies of choice. *Journal of the Experimental Analysis of Behavior*, *32*, 269–281.
- Bradshaw, C. M., Szabadi, E., & Bevan, P. (1976). Behavior in humans in variable-interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, *26*, 135–141.
- Conners, C. K. (1990). *Manual for Conners' rating scales*. North Tonawanda, NY: Multi-Health Systems, Inc.
- Cunningham, S. J., & Knights, R. M. (1978). The performance of hyperactive and normal boys under differing reward and punishment schedules. *Journal of Pediatric Psychology*, *3*, 195–201.
- Davison, M., & McCarthy, D. (1988). *The matching law: A research review*. Hillsdale, NJ: Erlbaum.
- DeLeon, I. G., & Iwata, B. A. (1996). Evaluation of a multiple-stimulus presentation format for assessing reinforcer preferences. *Journal of Applied Behavior Analysis*, *29*, 519–533.
- DiFonzo, N., Hantula, D. A., & Bordia, P. (1998). Microworlds for experimental research: Having your (control and collection) cake, and realism too. *Behavior Research Methods, Instruments, & Computers*, *30*, 278–286.
- Douglas, V. I. (1983). Attentional and cognitive problems. In M. Rutter (Ed.), *Developmental neuropsychiatry* (pp. 280–329). New York: Guilford Press.
- 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*, 313–326.
- Fleshler, M., & Hoffman, H. S. (1962). A progression for generating variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, *5*, 529–530.
- Fuqua, R. W. (1984). Comments on the applied relevance of the matching law. *Journal of Applied Behavior Analysis*, *17*, 381–386.
- Haenlein, M., & Caul, W. F. (1987). Attention deficit disorder with hyperactivity: A specific hypothesis of reward dysfunction. *Journal of American Academy of Child and Adolescent Psychiatry*, *26*, 356–362.
- Herrnstein, R. J. (1961). Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior*, *4*, 267–272.
- Herrnstein, R. J. (1970). On the law of effect. *Journal of the Experimental Analysis of Behavior*, *13*, 243–266.
- Heyman, G. M. (1992). Effects of methylphenidate on response rate and measures of motor performance and reinforcement efficacy. *Psychopharmacology*, *109*, 145–152.
- Heyman, G. M., & Monaghan, M. M. (1987). Effects of changes in response requirement and deprivation on the parameters of the matching law equation: New data and review. *Journal of Experimental Psychology: Animal Behavior Processes*, *13*, 384–394.
- Julien, R. M. (1998). *A primer of drug action: A concise, nontechnical guide to the actions, uses, and side effects of psychoactive drugs* (8th ed.). New York: Freeman.
- Kollins, S. H., Lane, S. D., & Shapiro, S. K. (1997). Experimental analysis of childhood psychopathology: A laboratory matching analysis of the behavior of children diagnosed with attention-deficit

- hyperactivity disorder (ADHD). *The Psychological Record*, 47, 25–44.
- Kollins, S. H., Newland, M. C., & Critchfield, T. S. (1997). Human sensitivity to reinforcement in operant choice: How much do consequences matter? *Psychonomic Bulletin and Review*, 4, 208–220.
- Mace, F. C. (1994). Basic research needed for stimulating the development of behavioral technologies. *Journal of the Experimental Analysis of Behavior*, 61, 529–550.
- Mace, F. C., Hock, M. L., Lalli, J. S., West, B. J., Belfiore, P., Pinter, E., & Brown, D. K. (1988). Behavioral momentum in the treatment of non-compliance. *Journal of Applied Behavior Analysis*, 23, 123–141.
- Mace, F. C., McCurdy, B., & Quigley, E. A. (1990). A collateral effect of reward predicted by matching theory. *Journal of Applied Behavior Analysis*, 23, 197–205.
- Mace, F. C., Neef, N. A., Shade, D., & Mauro, B. C. (1994). Limited matching on concurrent-schedule reinforcement of academic behavior. *Journal of Applied Behavior Analysis*, 27, 585–596.
- Mace, F. C., & Wacker, D. P. (1994). Toward greater integration of basic and applied behavioral research: An introduction. *Journal of Applied Behavior Analysis*, 27, 569–574.
- Martens, B. K., Halperin, S., Rummel, J. E., & Kilpatrick, D. (1990). Matching applied to contingent teacher attention. *Behavioral Assessment*, 12, 139–155.
- Martens, B. K., & Houk, J. L. (1989). The application of Herrnstein's law of effect to disruptive and on-task behavior of a retarded adolescent girl. *Journal of the Experimental Analysis of Behavior*, 51, 17–27.
- Martens, B. K., Lochner, D. G., & Kelly, S. Q. (1992). The effects of variable-interval reinforcement on academic engagement: A demonstration of matching theory. *Journal of Applied Behavior Analysis*, 25, 143–151.
- McDowell, J. J. (1982). The importance of Herrnstein's mathematical statement of the law of effect for behavior therapy. *American Psychologist*, 37, 771–779.
- Neef, N. A., Shade, D., & Miller, M. S. (1994). Assessing influential dimensions of reinforcers on choice in students with serious emotional disturbance. *Journal of Applied Behavior Analysis*, 27, 575–583.
- Northup, J., Fusilier, I., Swanson, V., Roane, H., & Borrero, J. (1997). An evaluation of methylphenidate as a potential establishing operation for some common classroom reinforcers. *Journal of Applied Behavior Analysis*, 30, 615–625.
- Northup, J., Jones, K., Broussard, C., & George, T. (1995). A preliminary comparison of reinforcer assessment methods for children with attention deficit hyperactivity disorder. *Journal of Applied Behavior Analysis*, 28, 99–100.
- Parry, P. A., & Douglas, V. I. (1983). Effects of reinforcement on concept identification in hyperactive children. *Journal of Abnormal Child Psychology*, 11, 327–340.
- Pelham, W. E. (1993). Pharmacotherapy for children with attention-deficit hyperactivity disorder. *School Psychology Review*, 22, 199–227.
- Pelham, W. E., Milich, R., & Walker, J. L. (1986). Effects of continuous and partial reinforcement and methylphenidate on learning in children with attention deficit disorder. *Journal of Abnormal Psychology*, 95, 319–325.
- Pierce, W. D., & Epling, W. F. (1983). Choice, matching, and human behavior: A review of the literature. *The Behavior Analyst*, 6, 57–76.
- Quay, H. C. (1997). Inhibition and attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology*, 25, 7–13.
- Rappaport, M. D., DuPaul, G. J., & Smith, N. F. (1985). Rate-dependency and hyperactivity: Methylphenidate effects on operant responding. *Pharmacology Biochemistry and Behavior*, 23, 77–83.
- Sagvolden, T., Aase, H., Zeiner, P., & Berger, D. (1998). Altered reinforcement mechanisms in attention deficit/hyperactivity disorder. *Behavioural Brain Research*, 94, 61–71.
- Saldana, L., & Neuringer, A. (1998). Is instrumental variability abnormally high in children exhibiting ADHD and aggressive behavior? *Behavioural Brain Research*, 94, 51–59.
- Wilkinson, G. N. (1961). Statistical estimations in enzyme kinetics. *Biochemical Journal*, 80, 324–332.

Received April 4, 2000

Final acceptance August 18, 2000

Action Editor, Robert Stromer

APPENDIX A  
Detailed Session Data for Derrek

Session	MPH or PL	Trial	VI schedule value	Length (min)	Problems completed	Problems correct	Problems per minute	% accuracy	Tokens earned
BL 1	None	3	6	10	194	194	19.4	100	61
		1	12		242	240	24.2	99.20	40
		4	20		216	214	21.6	99.10	34
BL 2	None	2	30	10	224	222	22.4	99.10	22
		1	6		251	249	25.1	99.20	65
		4	12		267	261	26.7	97.80	40
Day 1	PL	2	20	10	235	234	23.5	99.60	34
		3	30		220	217	22	98.60	22
		4	6		263	260	26.3	99.00	63
Day 2	MPH	1	12	10	231	230	23.1	99.60	40
		2	20		217	215	21.7	99.10	34
		3	30		215	210	21.5	97.70	22
Day 3	MPH	2	6	10	317	315	31.7	99.40	72
		4	12		314	312	31.4	99.40	40
		3	20		329	329	32.9	100	34
Day 4	PL	1	30	10	305	299	30.5	98.00	22
		1	6		395	392	39.5	99.20	81
		3	12		360	359	36	99.70	41
Day 5	PL	4	20	10	360	358	36	99.40	35
		2	30		375	374	37.5	99.70	22
		4	6		317	314	31.7	99.10	71
Day 6	MPH	2	12	10	279	278	27.9	99.64	40
		1	20		340	336	34	98.82	35
		3	30		288	285	28.8	98.96	22
Day 7	PL	4	6	10	302	301	30.2	99.67	71
		2	12		280	279	28	99.64	40
		3	20		310	309	31	100	34
Day 8	MPH	1	30	10	388	388	38.8	100	22
		2	6		396	392	39.6	98.99	78
		3	12		375	369	37.5	98.40	40
Day 9	PL	1	20	10	427	424	42.7	99.30	36
		4	30		371	367	37.1	98.92	23
		1	6		330	327	33	99.10	75
Day 10	MPH	2	12	10	275	269	27.5	97.82	40
		3	20		254	251	25.4	98.82	34
		4	30		256	252	25.6	98.44	22
Day 11	PL	2	6	10	416	412	41.6	99.01	80
		1	12		419	416	41.9	99.28	44
		4	20		323	316	32.3	97.83	36
Day 12	MPH	3	30	10	348	343	34.8	98.56	23

*Note.* MPH or PL refers to whether participants received methylphenidate or placebo for that day. Trial indicates the order in which schedule values were presented.

APPENDIX B  
Detailed Session Data for Willis

Session	MPH or PL	Trial	VI schedule value	Length (min)	Problems completed	Problems correct	Problems per minute	% accuracy	Tokens earned
BL 1	None	4	6	10	145	139	14.5	95.90	58
		1	12		191	188	19.1	98.43	40
		3	20		101	94	10.1	93.10	21
BL 2	None	2	30	10	154	148	15.4	96.10	10
		2	6		80	77	8	96.25	42
		3	12		64	62	6.4	96.88	26
Day 1	PL	1	20	10	125	125	12.5	100	22
		4	30		92	86	9.2	93.48	10
		1	6		140	137	14	97.86	62
Day 2	PL	2	12	10	96	92	9.6	95.83	35
		4	20		121	117	12.1	96.69	20
		3	30		99	95	9.9	95.96	10
Day 3	MPH	4	6	10	51	46	5.1	90.20	33
		3	12		56	51	5.6	91.10	25
		2	20		62	60	6.2	96.77	18
Day 4	MPH	1	30	10	100	96	10	96.00	10
		3	6		85	83	8.5	97.65	47
		4	12		57	53	5.7	92.98	25
Day 5	PL	1	20	10	125	116	12.5	92.80	20
		2	30		85	81	8.5	95.29	10
		1	6		89	84	8.9	94.40	52
Day 6	MPH	4	12	10	62	57	6.2	91.90	22
		3	20		81	77	8.1	95.10	17
		2	30		85	77	8.5	90.60	10
Day 7	MPH	4	6	10	76	73	7.6	96.05	34
		1	12		75	66	7.5	88.00	26
		2	20		43	36	4.3	83.70	12
Day 8	PL	3	30	10	60	53	6	88.30	9
		3	6		126	114	12.6	90.50	54
		2	12		106	94	10.6	88.68	33
Day 9	MPH	4	20	10	122	107	12.2	87.70	21
		1	30		62	56	6.2	90.32	9
		1	6		104	99	10.4	95.20	56
Day 10	PL	3	12	10	67	61	6.7	91.04	28
		2	20		41	37	4.1	90.24	15
		4	30		54	50	5.4	92.59	9
Day 11	MPH	2	6	10	126	112	12.6	88.88	60
		1	12		87	84	8.7	96.55	35
		4	20		111	99	11.1	89.20	21
Day 12	PL	3	30	10	75	71	7.5	94.67	10

*Note.* See Appendix A for details.

*STUDY QUESTIONS*

1. Describe matching theory and how its application may prove useful in describing the behavior of children diagnosed with attention deficit hyperactivity disorder.
2. What was the purpose of the study?
3. What was the target response, and how was the response format modified to facilitate discrimination among experimental conditions?
4. Describe the three goals of the screening assessment.
5. What type of experimental design was used to evaluate the effects of MPH and the reinforcement contingencies?
6. What features of the token-exchange system may have limited participants' sensitivity to reinforcement?
7. Summarize the data shown in Figures 3 and 4. What do these results suggest about the extent to which the matching equation described responding under MPH and placebo conditions?
8. Briefly describe some of the methodological limitations of the current study that might be addressed in future research.

Questions prepared by Juliet Connors and Claudia Dozier, The University of Florida