Journal of Abnormal Child Psychology, Vol. 17, No. 5, 1989, pp. 473–491

Effects of Methylphenidate on Inhibitory Control in Hyperactive Children

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This study investigated the effects of methylphenidate (MPH) on inhibitory control in hyperactive children. A double-blind, placebo-control, within-subject (crossover) design was used in which 12 children, between 6 and 11 years of age, were each tested four times in each drug condition: 0.3 mg/kg and 1.0 mg/kg of methylphenidate, and placebo. Dependent measures included (a) the probability of inhibiting responses to a primary choice reaction time task given a stop signal, on the Stopping Task, and (b) response latency and errors on the Matching Familiar Figures Test (MFFT). MPH improved the efficiency of the central inhibitory mechanism by speeding the inhibitory process, thereby affording the children greater control over their actions and enabling them to increase the probability with which they inhibited responses given a stop signal. MPH increased response latency but did not reduce errors on the MFFT, and observation of the children's task performance highlighted the interpretive problems associated with this task. Performance on both tasks was better at a dosage of 1.0 mg/kg than at 0.3 mg/kg.

Manuscript received in final form January 6, 1989.
This study was jointly funded by the Ontario Mental Health Foundation (Grant No. 963-86/88) and Health and Welfare Canada (NHRDP: Grant No. 6606-3166-42). We wish to thank Patricia Fulford and Haroldine Phair for their assistance in data collection, the children and parents who participated in this study, the referring physicians, and the pharmacy department at the Hospital for Sick Children for preparation of prescriptions.
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0091-0627/89/1000-0473$06.00/0

Psychostimulants, such as methylphenidate (MPH), are believed to activate central self-regulatory or control process, thereby ameliorating one of the fundamental problems of hyperactive children[4] – a deficit in inhibitory control (Douglas, 1984). Control processes are "executive functions" of the cognitive system that determine how various mental processes (e.g., encoding, recognition, retrieval) will work together to perform a task. Executive control is required for the choice, construction, execution, and maintenance of optimal strategies for performing a task, as well as for the inhibition of strategies that become inappropriate with changes in goals or in task demands, or with the occurrence of errors (Logan 1985). A deficit in inhibitory control is manifested in a range of impulsive symptomatology, such as the tendency to act before understanding the task, or to give an answer without giving sufficient consideration to other possible solutions.

The hypothesized enhancement of executive control by psychostimulants is compatible with the finding that MPH reduces symptoms of impulsive behavior in hyperactive children, according to parent and teacher ratings (e.g, Rapport et al., 1988). Moreover, stimulant medication improves the performance of hyperactive children on a range of laboratory-based measures of impulsivity (e.g., Douglas, Barr, Amin, O'Neill, & Britton, 1988; Rapport et al., 1988). A basic problem with most of these measures, however, is that they are not defined in terms of underlying psychological processes. The ability to inhibit is not measured directly but must be inferred from measures of performance style. For example, fast but inaccurate performance on the Matching Familiar Figures Test (MFFT; Kagan, Rosman, Day, Albert, & Phillips, 1964) is assumed to indicate impulsivity or deficient cognitive control in response inhibition. However, most of these traditional measures of childhood impulsivity involve a complex web of cognitive functions (Messer, 1976; Milich & Kramer, 1984; Block, Gjerde, & Block, 1986). Thus, stimulant-induced changes in task performance could result from changes in other functions, such as visual search strategies (e.g., Ault, Crawford, & Jeffrey, 1972) or decision criteria, without any change in inhibitory control.

This study was designed to provide a more rigorous investigation of the hypothesized effects of MPH on inhibitory control, by using a novel paradigm that affords direct assessment of the mechanism underlying the ability to inhibit. The *stop-signal paradigm* is derived from a theory of inhibition that accounts for people's performance in situations requiring a stop or change in their current thoughts and actions (Logan & Cowan, 1984). The theory proposes that a control signal, such as an error during performance or an external warning or stop signal, initiates an inhibitory process that races

[4]The generic term *hyperactive* is used throughout this paper to refer to children with a DSM-III (American Psychiatric Association, 1980) diagnosis of attention deficit disorder with hyperactivity.

against the process underlying the ongoing thought or action. If the inhibitory process wins, thought and action are inhibited; if the ongoing process wins, then thought and action run to completion. In the latter case, the individual's inability to stop their current thought or action results in impulsive behavior.

The stop-signal paradigm provides a laboratory analogue of situations that elicit impulsive behavior. While subjects are engaged in a primary task (usually a forced-choice letter discrimination task), they are presented with an occasional stop signal (usually a tone), which instructs them to inhibit their response to the primary task if they can. The primary-task stimuli simulate the class of stimuli that elicit impulsive behavior, whereas the stop signals simulate those that initiate the inhibitory process. The main dependent variable is the probability of inhibiting (P-inhibit) the primary-task response when given a stop signal. The main independent variable is the delay between the stop signal and performance of the primary task; when the stop signal occurs early enough, subjects always inhibit (i.e., P-inhibit = 1.0); if it occurs late enough, subjects never inhibit (i.e., P-inhibit = 0.0). The shape of the inhibition function, generated by plotting the probability of inhibition against stop-signal delay, reflects the efficiency of the inhibitory mechanism. Essentially, the steeper and higher the function, the better the inhibitory mechanism.

In impulsive children, the inhibitory mechanism may be deficient in at least two ways. First, it may fail to be triggered by the stop signal, as if the child never tried to inhibit the response. Second, the inhibitory mechanism may be triggered on each stop-signal trial, but its response may be slower than normal. Larger variance may be associated with the slower speed, as is often the case with overt reaction times (e.g., Luce, 1986). In all cases, the resulting inhibition function would be lower and flatter than a normal one (for complete explanation see Logan & Cowan, 1984). Of relevance here is the finding that the inhibition functions of hyperactive children are lower and flatter than those of normally developing children (Schachar & Logan, 1988).

If psychostimulants improve the efficacy of the inhibition mechanism, it may do so by increasing the probability with which the mechanism is triggered by the stop signal, by speeding up the inhibitory process (and making it less variable), or by both means. Any of these effects would result in steeper and higher inhibition functions on MPH than on placebo.

To integrate the results from the stop-signal paradigm with previous research on stimulant effects on inhibitory control, we included a conventional measure of this construct—the MFFT (notwithstanding its problems for interpretation). This task requires the subject to search through a set of similar pictures for the variant that matches a criterion picture exactly. Thus, to avoid errors, the subject must inhibit responding until all variants have

been checked. The demand for response inhibition may be manipulated by increasing the number of variants. Rovet (1980) and Yando and Kagan (1970) found that impulsive (but not necessarily hyperactive) children responded quickly before considering all the possible options, and thus made more errors with increasing number of variants, but failed to show increasing response latencies. In contrast, reflective children increased their response latencies, and did not make more errors with more variants. This study improves upon previous investigations of stimulant effects on MFFT performance by including this manipulation of response inhibition. The MFFT performance of hyperactive children was expected to mirror that of the impulsive children: Errors but not response latencies will increase as a function of the number of variants. Also, since response latency and accuracy are believed to be conjoint indices of impulsivity, we expected children with the lowest and flattest inhibition functions to exhibit the shortest latencies and highest errors. Treatment with MPH was expected to increase latency and decrease errors, as a function of the number of variants.

We examined the effect of two dosages of MPH (a low dosage of 0.3 mg/kg and a high dosage of 1.0 mg/kg) in order to examine dose-response functions for inhibitory control. The dosages were selected to reflect the dosage range observed in clinical practice, and the range used in previous research on stimulant effects on impulsivity.

METHOD

Subjects

A total of 12 children (10 males, 2 females) between the ages of 6 and 11 years (M = 8.4 years, SD = 1.4 years), with an established diagnosis of attention deficit disorder with hyperactivity (ADDH), participated with the informed consent of their parents and assent from the child. Children were recruited for the project from children referred to the psychiatric outpatient department at the Hospital for Sick Children, and from physicians in the Toronto metropolian area. To be eligible, children had to exhibit symptoms of inattention, impulsiveness, and hyperactivity that were considered by the referring physician to be of sufficient severity to warrant consideration of a trial with stimulant medication. The children were all of average or above average intelligence (Mean IQ = 105, SD = 14.0) as estimated on the WISC-R. As might be expected in a sample of children with ADDH (Lambert & Sandoval, 1980), many of them (n = 8) exhibited learning disabilities according to teacher report and as indicated by scores below the 25th percentile on one or more of the subtests of the Wide Range Achievement Test-Revised (WRAT-R); Siegel & Heaven, 1986). Four children also met the DSM-

III (American Psychiatric Association, 1980) criteria for oppositional disorder. Eight of the children had received stimulant medication previously and 3 of these were receiving it at the time of referral. The regular dose was discontinued for these latter children at least 48 hours prior to the diagnostic assessment and 72 hours prior to participation; it was not reinstated until the completion of the trial. The mean weight of the children was 29 kg (range 17–49 kg).

A diagnosis of ADDH was established from information derived from the referring physician, a semistructured interview with the child's parents conducted by a child psychiatrist using the Parent Interview for Child Symptoms (PICS; Schachar & Wachsmuth, 1984), and behavior ratings completed by the child's teacher. The PICS covers the child's developmental, medical, and psychiatric history, and contains 110 items designed to elicit parental descriptions of the child's current behavior in a variety of specific situations (e.g., playing games indoors and outdoors, mealtimes at home and in restaurants). The absence/presence and severity of the behavioral symptoms in the specific situations are then rated by the interviewer. This semistructured interview covers all the details necessary to apply DSM-III diagnoses of ADDH, conduct, oppositional, affective, anxiety, and psychosomatic disorders. Agreement between two psychiatrists rating the same interview ($N = 20$) was high for ratings of individual symptoms (Kappa = .95). None of the disagreements that occurred resulted in different diagnoses being applied by the psychiatrists. Each child's classroom teacher was asked to complete the Abbreviated Conners Teacher Questionnaire (Conners, 1973), the Rutter-B questionnaire (Rutter & Graham, 1968), and SNAP questionnaire (Pelham, Atkins, & Murphy, 1981).

A diagnosis of ADDH was made if the child demonstrated at least three symptoms of inattentiveness, three impulsive, and two overactive symptoms, with a history of these symptoms before 6 years of age, based on the parential interview (PICS). Since ADDH may be diagnosed on the basis of teacher report alone (American Psychiatric Association, 1980), a diagnosis of ADDH was made if the child received a Rutter-B total score of 9 or more (a score predictive of clinical diagnosis of a psychiatric disorder; Rutter, Tizard, & Whitmore, 1970) and fulfilled any two of the following criteria: (1) a score of 15 or more on the Abbreviated Conners Teacher Questionnaire (a score predictive of a clinical diagnosis of hyperactivity; Goyette, Conners, & Ulrich, 1978); (2) at least four inattentive, four impulsive, and three overactive symptoms on the SNAP (a score obtained by 5% of 10-year-old boys; Pelham et al., 1981); or (3) a score of 5 or 6 on the Rutter-B hyperactivity factor (a score obtained by 3% of 10-year-old boys; Schachar, Rutter, & Smith, 1981). The mean score on the Conners was 20.4 ($SD = 5.3$).

Children with a full scale WISC-R score of less than 80, with an exclusive DSM-III diagnosis of emotional or conduct disorder, and/or with major

neurological, physical, or sensory impairment were excluded. An additional four children who were referred to the project did not participate. Two of these children met the DSM-III criteria for aggressive conduct disorder but not for ADDH, one child did not meet the intellectual criteria, and one refused to participate.

Experimental Design, Drug Administration

A multiple-blind, placebo-control, within-subject (crossover) design was used in which each child received each of placebo, low dose of MPH (0.3 mg/kg), and high dose of MPH (1.0 mg/kg) on four occasions across a 6-day period. The order of drug condition was randomized with the restrictions that each child receive two different drug conditions each day, and that the three drug conditions (placebo, low dose, high dose) occur with equal frequency in the morning and afternoon. The resulting six possible combinations are listed in Table I. The order of these six combinations was randomized for each child. This rapid and random alternating treatments design takes advantage of the relatively short half-life of MPH (i.e., 2–3 hours: Swanson, Kinsbourne, Roberts, & Zucker, 1978). An interval of 4 hours separated the morning and afternoon dose.

The MPH and placebo were packaged in colored gelatin capsules, to avoid detection of dose and taste, and were dispensed by project staff 1 hour prior to each testing session.

Procedure

Each child attended the research department with the parents for a half-day assessment session. While the parents were interviewed by a child psychiatrist, the child was familiarized with the staff and testing procedures, and practiced the tasks to be used during the medication trial. In addition to obtaining informed consent from the parents, consent was secured to obtain the child's scores on the WISC-R and WRAT-R (Jastak & Wilkinson,

Table I. Combinations of Drug Conditions[a]

	Combination					
	1	2	3	4	5	6
a.m. dose	P	P	L	L	H	H
p.m. dose	H	L	H	P	L	P

[a] *P* = placebo, *L* = low dose (0.3 mg/kg), *H* = high dose (1.0 mg/kg).

1984). If these tests had not been administered in the past year ($n = 5$), all three subtests of the WRAT-R and the vocabulary and block design subtests of the WISC-R were administered.

A total of 12 test sessions were conducted with each child over 6 days (i.e., 2 sessions each day). Children were tested individually, and medication was timed so that test data were collected during the period 60 to 120 minutes postingestion, to ensure maximum medication effect (Swanson et al., 1978). Blood pressure and pulse readings were taken immediately before and 1 hour after receiving the medication. The child was monitored for adverse side effects (e.g., pallor, nausea, decrease in appetite, stereotypic movements, tics) throughout the day by a nurse. The order of tasks was kept constant for all testing sessions; the stopping task, which took approximately 45 minutes (with short breaks), was completed prior to the MFFT, which lasted between 5 and 15 minutes.

Tasks

Stopping Task. This task, developed by Logan and his colleagues (Logan, Cowan, & Davis 1984; Logan & Cowan 1984), is an experimenter-paced choice reaction time task that examines the ability to inhibit responses to a primary task given a stop signal. The stimuli consisted of the uppercase letters *X* and *O*, presented via an Apple IIe computer that was connected to a specialized Cognitive Testing Station (CTS; Digitry Company Inc., 1984). The CTS software allowed direct and precise control of the stimulus presentation as well as the collection of reaction times (RT) with millisecond timing. Each letter, presented one at a time in the center of the screen, was 2 mm wide and 5 mm high. When viewed at a distance of 40 cm, each letter subtended .29° × .72° of visual angle. The stop signal was an auditory tone (a "beep") generated and presented via the Apple IIe computer. It was presented on 25% of the trials of the primary task, occurring a total of 18 times at each of the 6 delays, and equally often with an *X* and an *O*. Details of the delays and the manner in which they were generated are discussed later.

Each trial began with a fixation point illuminated for 500 ms. It was followed by the letter for that trial, which was displayed for 1 sec and then extinguished. The screen remained blank for an intertrial interval of 1.5 sec. The child responded to the letter by pressing one of two keys on a response box that was connected to the CTS hardware. Mapping of the letters onto the keys was randomized among subjects, but the mapping was kept constant for the child for every test session.

Stop signals were presented at delays defined relative to each child's mean reaction time (MRT) to the primary task (see Logan & Cowan, 1984, for discussion on determination of stop-signal delays). The six top-signal

delays in the present study were calculated to be equal to MRT-500 ms, MRT-400 ms, MRT-300 ms, MRT-200 ms, MRT-100 ms, and MRT-0 ms. Whereas it is almost impossible to inhibit a response to a stop signal presented at one's MRT, the more the signal precedes MRT, the greater the probability of inhibition. At each testing session a total of 528 trials were presented, in 11 blocks of 48 trials. The first block of trials consisted of practice trials for the choice reaction task alone, while the second served as practice for the stopping task. Mean reaction time (MRT) calculated in the first block was used to set stop signals at the six delays for the second block. MRT for nonsignal trials for the second block was then used to set the delays for the third block, and so on. The sequence of letters, stop signals, and stop signal delays was random, and a different random order was prepared for each child at each session. The 9 blocks of test trials were arranged in groups of three, and a short break was scheduled after each part. The task lasted from 35 to 45 minutes depending upon the length of break between the parts. The dynamic tracking of each child's mean reaction time and concomitant adjustment of stop-signal delays meant that delays for a given block depended only upon performance in the immediately preceding block. The probability of response inhibition being influenced by strategy choice (e.g., holding back response to see if signal occurred) or by medication-induced changes in primary task reaction time was thereby reduced (see Logan et al., 1984).

Instructions for the choice reaction time task were given first. Children were told to respond as quickly and accurately as possible. Following the block of practice trials the children were then instructed to try to stop their response to the task whenever the "beep" occurred. They were also told not to wait for the stop signal before responding since it did not occur very often.

The following dependent variables were measured: probability of response inhibition at each of the six stop-signal delays; reaction time to the primary task for nonsignal trials; percentage of commission errors (pressing for *X* when *O* was presented or vice versa); and percentage of omission errors (i.e., not responding to the primary task despite the absence of a stop signal). Also, the internal reaction time to the stop signal (SSRT) was estimated for each subject at each test session (for derivation, see Logan et al., 1984).

Matching Familiar Figures Test. A 16-item version of the MFFT, with figures redrawn from the original Yando and Kagan (1970) series, was used in the present study. This version consisted of 4 test items at each of the four sizes of response set (3, 4, 6, and 8 variants) plus two practice trials. These 16 test items were arranged in random order in a booklet. Equivalent versions were constructed for use in the 12 test sessions, by rearranging the location of the variants and by altering features in the target stimulus and in the variants. The order of the equivalent versions was randomized separately for each subject. Standard instructions were used in administering the tasks.

Scores were based on the total number of incorrect choices and the mean latency of first response choice calculated across the four trials in each response set size.

Statistical Analysis

Scores were based on the average score for each subject obtained in the four test sessions at each drug condition. Analysis of variance (ANOVA) with repeated measures across the three medication conditions (placebo, low and high dose MPH) was performed on the computed mean score for each dependent variable. For all measures in which the overall F value (using Greenhouse-Geisser Correction) was significant, post hoc Newman-Keuls tests (Winer, 1971) were conducted in order to determine the location of differences between medication conditions.

Adjustments to P-Inhibition. Two adjustment procedures were used to account for potential effects of omission errors and primary task MRT variance on the probability of inhibition, although in adults such effects have been small (Logan et al., 1984).

1. Omission errors may result from off-task behavior or from adoption of a response strategy in which subjects attempt to increase P-inhibition by deciding before the trial not to respond, independent of stimulus events. Since some of these omissions may occur on stop-signal trials, the observed P-inhibition may reflect both omissions and true response inhibition. This effect extended across all stop-signal delays would increase the height and steepness of inhibition functions. Since many children ($n = 6$) exhibited over 5% omissions errors, particularly with placebo, P-inhibition at each delay was corrected for the percent of omissions observed on nonsignal trials, using the following formula:

$$y = \frac{x - p}{\mathrm{i} - p}$$

where y is the corrected P-inhibition at a specific delay, x is the observed P-inhibition at that delay, and p is the overall probability of omissions (i.e., not responding to the primary task on nonsignal trials). All analyses were conducted on the adjusted probability of inhibition.

2. Since MPH typically reduces MRT variability (e.g., Peloquin & Klorman, 1986; Coons, Klorman, & Borgstedt, 1987), which, in turn affects inhibition functions, we needed to separate stimulant effects on the primary task response process from its effects on the inhibitory process. Differences in MRT variance may be controlled by plotting P-inhibition as a function

of the relative finishing time (RFT) of the inhibitory process and primary task process, expressed as a *Z* score (ZRFT) relative to the standard deviation of the primary task MRT (for derivation, see Logan et al., 1984). If the inhibition functions from placebo, and MPH conditions cannot be aligned by plotting them as a function of ZRFT, then we can conclude that steeper functions obtained with MPH reflect its effect on the central inhibitory process. Regression lines were fitted to the data sets for P-inhibition as a function of ZRFT, for each subject at each test session. The average values for the slope of the regression lines, calculated for each individual in each medication condition, were then entered into a univariate analysis of variance with repeated measures across drug condition.

Analysis of Carryover Effects. The design was predicated on the assumption that stimulant effects will have essentially dissipated within 4 hours, since the estimated behavioral and plasma half-life is 2 to 3 hours (Swanson et al., 1978; Gualtieri et al., 1982). There is a possibility, however, that effects of the morning condition may persist into the afternoon, the most likely situation being from a morning dose of 1.0 mg/kg to an afternoon condition of placebo or 0.3 mg/kg. Such effects may artifically inflate scores in the afternoon condition and attenuate differences between conditions. Carryover effects from a morning dose of 1.0 mg/kg on placebo performance in the afternoon, were examined in an ANOVA comparing all four placebo sessions, conditional upon the antecedent or consequent medication condition. Thus, session A constituted placebo performance in the afternoon given a preceding dose of 1.0 mg/kg in the morning; session B was afternoon placebo performance given a morning dose of 0.3 mg/kg; session C was morning placebo performance when followed by a 1.0 mg/kg dose in the afternoon; and session D was morning placebo performance when followed by 0.3 mg/kg. The order of the four sessions had been randomized across children. Also, carryover effects from a morning dose of 1.0 mg/kg on the afternoon performance at 0.3 mg/kg was examined in a similar manner in a separate comparison of all four low-dose sessions. If carryover effects exist, then either session A or B, or both, would differ from sessions C and D.

RESULTS

Inhibitory Process. Figure 1 displays the mean probability of inhibition as a function of stop-signal delay for each drug condition. A two-way analysis of variance with repeated measures across drug condition (3 levels) and stop-signal delays (6 levels) was conducted for the probability of inhibition to stop signals. As shown in Figure 1, the probability of inhibiting given a stop signal increased with stop-signal delay ($F(5, 55) = 30.9$, $p < .01$)

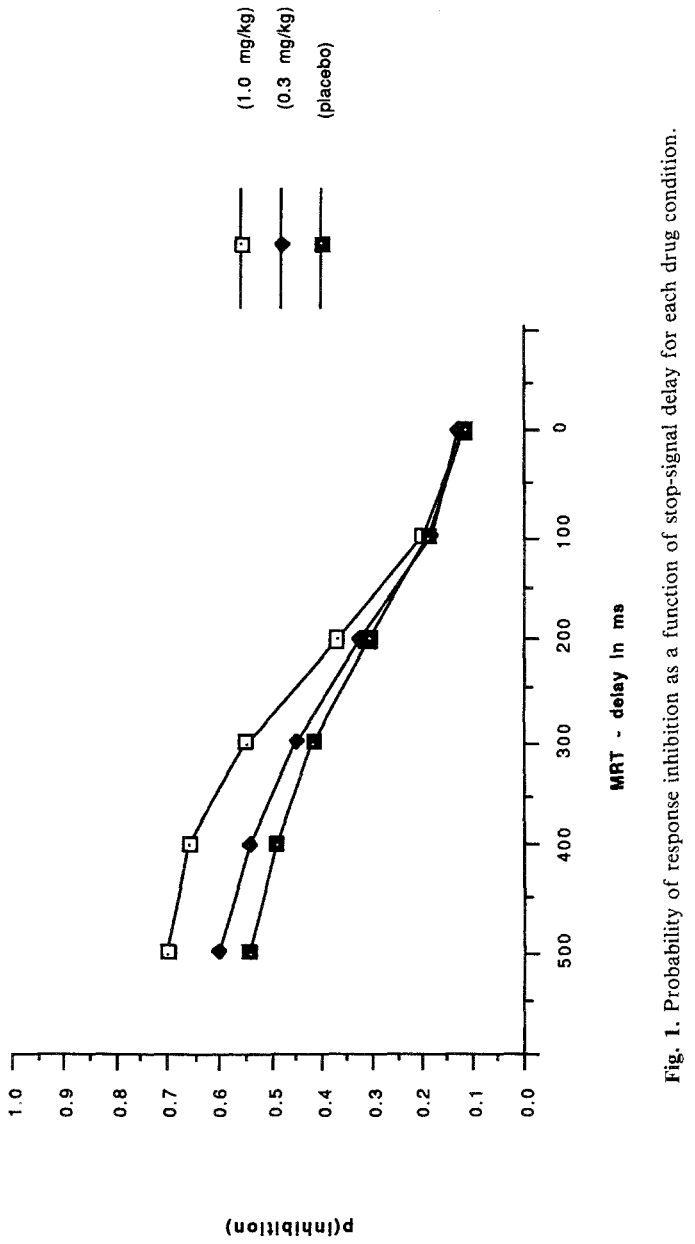

Fig. 1. Probability of response inhibition as a function of stop-signal delay for each drug condition.

across all drug conditions. Of greater interest is the significant main effect obtained for drug ($F(2, 22) = 15.66, p < .01$), which signifies that the inhibition functions observed with MPH were higher than those observed in placebo condition. Also, the significant interaction between drug condition and signal delay ($F(10, 110) = 5.36, p < .01$) suggests that the inhibition functions observed with MPH were steeper as well as higher than those observed at placebo. We were concerned with the linear component of the interaction, which was tested in a one-way analysis of variance of the slope of the inhibition functions, plotted as a function of ZRFT, with repeated measures across drug condition. The significant main effect for drug ($F(2, 22) = 3.64$, $p < .05$) confirmed not only that the inhibition functions observed with methylphendiate were steeper than those observed in placebo condition but also that this effect was not an artifact of differences in the variance of primary task reaction time that were produced by MPH (see below). Post hoc Newman-Keuls tests (Winer, 1971) revealed that the slopes obtained at 1.0 mg/kg were significantly steeper than those at 0.3 mg/kg ($p < .05$) or placebo ($p < .05$). The slopes obtained at 0.3 mg/kg and placebo did not differ.

MPH speeded the inhibitory process: Main effects for drug were found for the internal reaction time to the stop signal (SSRT) ($F(2, 22) = 6.28$, $p < .01$). Post hoc Newman Keuls tests indicated that the inhibitory process was significantly faster at 1.0 mg/kg than at 0.3 mg/kg or placebo ($p < .05$), but there was no difference in its speed at placebo or 0.3 mg/kg. Mean values for the inhibition function slopes and SSRT are presented for each drug condition in Table II.

Primary-Task Response Process. Univariate analyses of variance were conducted separately for mean reaction time (MRT) to the nonsignal trials on the primary task, the standard deviation of MRT, the percentage of commissions on the choice reaction time task, and the percentage of omissions. Means for each of these dependent measures in each drug condition are presented in Table II. Significant main effects for drug were obtained for MRT ($F(2, 22) = 8.62, p < .01$), standard deviation of MRT ($F(2, 22) = 16.77, p < .01$), and percent of omissions ($F(2, 22) = 3.54, p < .05$), but

Table II. Means for Dependent Measures from the Stopping Task for Each Drug Condition

Dependent variable	Placebo	0.3 mg/kg	1.0 mg/kg
Slope of inhibition function (ZRFT)	19.6	20.2	23.9
Stop signal reaction time in ms (SSRT)	353.8	351.0	297.4
Mean reaction time to primary task in ms (MRT)	903.7	840.9	802.1
Standard deviation of MRT	307.7	256.3	224.0
Percent omissions on primary task	8.7	5.3	3.6
Percent commissions on primary task	9.3	8.1	7.5

the effect for percent of commissions was only marginally significant ($F(2, 22) = 3.36$, $p < .053$).

Subsequent post-hoc Newman-Keuls tests revealed that MRT was significantly improved (i.e., faster) following both dosage levels of MPH compared with placebo ($p < .05$), but the advantage afforded by the high dose over the low was not significant. The standard deviation of MRT was significantly improved (i.e., decreased) by both the high and the low dosage of MPH, compared with placebo ($p < .05$), and was further improved by the 1.0 mg/kg dose compared with the 0.3 mg/kg dose ($p < .05$). The percent of no responses was significantly less under the high dose compared with placebo ($p < .05$).

MFFT. A two-way ANOVA with repeated measures across dose (3 levels) and number of variants (4 levels) was conducted separately for errors and latency. For MFFT latency, the main effect for drug was not statistically significant, but there was a significant overall effect for number of variants ($F(3, 33) = 10.2$, $p < .01$) and a significant interaction between drug and number of variants ($F(6, 66) = 2.37$, $p < .05$). The trend across variants was one in which response latency increased from 3 and 4 variants to 6 variants across all drug conditions (see Figure 2), but there was an unexpected decrease in latency with 8 variants. Post hoc comparisons revealed that latency was longer for 6 variants than for 4 ($p < .05$) or 3 ($p < .05$) variants following placebo administration. Both the 0.3 mg/kg and 1.0 mg/kg dosages of MPH resulted in substantial changes in response latency as a function of the number of variants; with both dosages, latency was longer with 6 variants than with 8 variants ($p < .01$), 4 variants ($p < .01$), and 3 variants ($p < .01$); latency was longer on the 8-variant set than on the 4 variants ($p < .01$) and 3 variants ($p < .01$). The 6-variant set was the most sensitive to dosage effects; 1.0 mg/kg results in significantly longer latencies than 0.3 mg/kg, which in turn resulted in longer latencies than at placebo ($p < .01$). With 8 variants, latencies were longer at 1.0 mg/kg than placebo ($p < .05$).

Analysis of the MFFT errors indicated that the reduction in errors across drug conditions failed to reach conventional levels of statistical significance, as did the interaction between number of variants and drug condition. The main effect for the number of variants was significant ($F(3, 33) = 16.57$, $p < .01$), signifying an increase in errors with an increasing number of variants. Significantly more errors were made with 8 and 6 variants than with 4 or 3 variants ($p < .01$). A moderate negative correlation (Spearman rank, $r = -.50$), was obtained between MFFT errors and latency.

Magnitude of Treatment Effects. Omega-squared values (Keppel, 1982) were calculated separately for the significant ANOVAs to estimate the percentage of the variance of each dependent measure that was attributable to the effect of treatment with the stimulant medication. These values indicat-

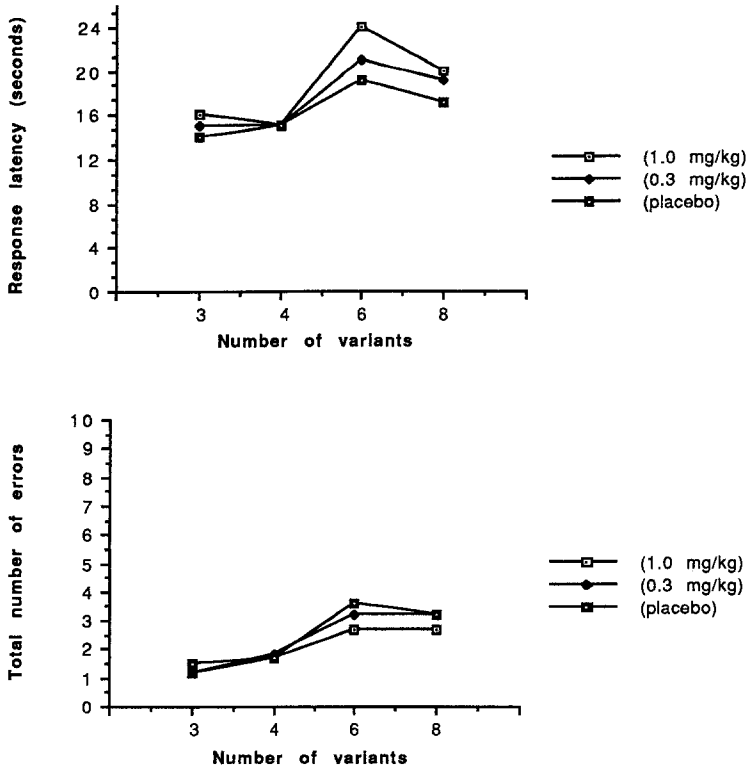

Fig. 2. Response latency and errors on the MFFT as a function of number of variants for each drug condition.

ed that MPH accounted for a substantial amount of the variance of the speed of the inhibitory process (i.e., SSRT, 23%), the variance of SSRT (46%), the primary task MRT (30%), and MRT variability (47%), and accounted for a moderate amount of the variance of omissions (15%). Also, MPH accounted for 13% of the variance of the steepness of the inhibition function, after accounting for the stimulant-induced differences in the variance of primary task reaction time. In contrast, the stimulant accounted for only 1% of the variance of MFFT errors and latency.

Relations Between Inhibitory Control and MFFT Performance. Spearman rank correlations were conducted between the slope of the inhibition function and MFFT error and latency scores. A low negative correlation ($r = -.38$) was obtained for inhibition function and MFFT error, but inspection of the scattergram revealed that with one exception, children with flatter inhibition functions tended to exhibit higher errors. The outlier obtained

one of the steepest inhibition functions but exhibited the most errors. Elimination of the outlier revealed the strength of the association ($r = -.66$). There was no discernible pattern of association between the inhibition function and MFFT latency from either the correlation ($r = .14$) or the scattergram.

Carryover Effects. A one-way analysis of variance with repeated measures across sessions (4 levels: A, B, C, D) was conducted separately for the slopes of inhibition functions and primary-task MRT. There was no evidence of carryover effects from a morning dose of either 1.0 mg/kg or 0.3 mg/kg to the afternoon placebo condition; neither were there any carryover effects from a morning dose of 1.0 mg/kg to the afternoon condition of 0.3 mg/kg,

DISCUSSION

The results of this investigation support the hypothesis that MPH improves the executive function of inhibitory control. Since the inhibition function obtained with MPH was significantly higher and steeper than that observed in the placebo condition, and since these functions could not be aligned by plotting them against ZRFT, we can conclude that MPH improves the efficacy of the central inhibitory process. It did so by speeding up the inhibitory process and increasing the probability with which the mechanism was triggered given a stop signal. In a previous study using the stop-signal paradigm, we found that the inhibition functions of hyperactive children were significantly flatter than those of normally developing children and of children with other disorders in the absence of hyperactivity (e.g., emotional disturbance, conduct disorders, learning disorders), signifying a specific deficit in inhibitory control (Schachar & Logan, 1988). This deficit is manifested in a range of impulsive behaviors. The present findings demonstrate that MPH improves the executive process underlying one of the major symptoms of hyperactive children—that of impulsiveness.

In addition to the stimulant-induced improvement in the inhibitory process, MPH also improved the primary-task response process: Children responded significantly faster, with less variability, and without loss of accuracy (i.e., fewer omissions and commission errors on the primary task). Since the underlying theory of inhibition of action and thought is predicated on the assumption that the two processes (stopping process and response process) are independent and do not compete for resources, concomitant changes in the primary task process are not necessarily expected. The observed improvement in the primary task process suggests that MPH may also enhance the executive functions involved in the selection, execution, or maintenance of an optimal response strategy. Alternatively, since psychostimulants

increase arousal (e.g., Rapport et al., 1978), and arousal may increase attentional capacity (Kahneman, 1973), the observed improvement in performance may be attributable to a stimulant-induced increase in attentional capacity. Thus, the beneficial effects of MPH may not be limited to inhibitory control but may extend to a range of executive functions or even increase attentional capacity. The latter hypothesis might account for reports of stimulant-related improvements on a wide range of cognitive tasks. This study was designed to investigate the effect of MPH on inhibitory control and not to disentangle competing hypotheses. Although further studies are required to investigate the effect of psychostimulants on other executive functions and on attentional capacity, our results provide clear evidence of MPH-induced enhancement of the central inhibitory function.

The effects of MPH on MFFT performance were less clear, suggesting that MFFT latency and error measures were less sensitive to medication effects than were measures derived from the stopping task. We were interested in the effects of MPH on MFFT performance as a function of increasing demand for response inhibition. The placebo level performance of the hyperactive children in this study indicated that, like the impulsive children in the studies by Rovet (1980) and Yando and Kagan (1970), they made more errors with increasing number of variants, but like the reflective children in those studies, they took longer to respond as the number of variants increased. Treatment with MPH resulted in longer response latency and decreased errors (albeit nonsignificantly), as a function of an increasing number of variants. Somewhat surprisingly, the hyperactive children responded more quickly on the largest (8-variant) response set than on the 6-variant set, although they made a similar number of errors on both of these sets. A systematic analysis of the children's task strategies was not conducted, but observation of the children's performance suggested that they changed strategies when faced with 8 variants to consider, particularly when medicated. With 8 variants, the children tended to quickly eliminate a number of variants and then proceed to compare the remaining variants with the standard figure, whereas with 6 variants they tended to keep all the variants as possibilities. These observations highlight the interpretive problems associated with changes in MFFT performance. The dearth of information about underlying cognitive processes involved in MFFT performance obscures any interpretation of change scores in latency or errors.

In contrast to the findings of Brown and colleagues (Brown & Sleator, 1979; Brown, Slimmer, & Wynne, 1984), which have frequently been interpreted as evidence that cognitive processes are improved by low dosages of 0.3 mg/kg but impaired by high dosages of 1.0 mg/kg, optimal improvement in inhibitory control in this study was obtained at 1.0 mg/kg rather than at 0.3 mg/kg. Similarly, there was no evidence of a dose-related deteri-

oration in performance on the primary task or on the MFFT. The absence of an intermediate or moderate dosage (e.g., 0.6 mg/kg) in our study prevents us from concluding that the relationship between dosage and inhibitory control is linear. Evidence from other studies using various performance measures of impulsiveness, such as the number of anticipatory responses on delayed reaction time tasks (e.g., Solanto & Conners, 1982; Douglas et al., 1988), suggests that the relationship between increasing dosage and impulsive performance style may be linear across the range of dosages from 0.15 to 1.0 mg/kg. These measures are, however, subject to the same problems of interpretion discussed earlier in this paper.

The stopping task and the MFFT both purport to yield measures of impulsivity, and as hypothesized, a substantial negative correlation was obtained between the slope of the inhibition function and MFFT errors, signifying that children with a deficient inhibitory process, as measured by the stopping task, tended to make the most errors on the MFFT—probably because they failed to check all of the variants carefully before responding. In contrast, there was no discernible relation between the slope of the inhibition function and MFFT latency, suggesting that latency may reflect processes other than response inhibition. Although both tasks were sensitive to MPH in that performance looked less impulsive with medication than with placebo, the stopping task provided a more interpretable picture. Measures yielded by the stopping task are defined in terms of underlying psychological processes, and thus, stimulant-induced changes in performance on it reflect stimulant effects on the inhibitory process itself. Moreover, the greater sensitivity of the stopping task to MPH is reflected in the Omega-squared values, which indicate the proportion of variance in scores accounted for by medication.

In summary, the major finding was that MPH improved the central inhibitory process in hyperactive children, enabling them to inhibit inappropriate, discrete motor responses when given an overt signal to do so. In daily activities, however, the stopping process must often be initiated by an internally generated signal, such as recognition of an error during performance, rather than an external signal as used in the stop-signal paradigm. Thus, a critical issue is the extent to which this finding can be generalized to the control of other actions in other situations. Findings from previous studies using the stop-signal paradigm with adults indicate that inhibition functions differ very little across strategies and tasks (e.g., Logan, 1981; Logan & Cowan, 1984). Moreover, improvements in hyperactive children's control of impulsive behaviors in the classroom following treatment with MPH are well documented (e.g., Rapport et al., 1988). Collectively these findings suggest that MPH may afford close control over a range of actions in various situations. The data also suggested that the salutary effect of MPH may be not

be limited to inhibitory control but may extend to other executive functions, or even to attentional capacity. Improvement in performance on academic and cognitive tasks depends not only on the ability to inhibit or disengage inappropriate strategies but also on the ability to reengage optimal ones. Further studies are required to investigate the effects of MPH on other executive functions, including those involved in the choice, execution, and maintenance of optimal strategies, and on attentional capacity. A more precise understanding of the effects of MPH will afford better prediction of response to stimulant treatment.

REFERENCES

American Psychiatric Association. (1980). *Diagnostic and statistical manual of mental disorders* (3rd ed.). Washington, DC: Author.

Ault, R. L., Crawford, D. E., & Jeffrey, W. E. (1972). Visual scanning strategies of reflective, impulsive, fast-accurate, and slow-accurate children on the Matching Familiar Figures Test. *Child Development, 43,* 1412-1417.

Block, J., Gjerde, P. F., & Block, J. H. (1986). More misgivings about the Matching Familiar Figures Test as a measure of reflection-impulsivity: Absence of construct validity in preadolescence. *Developmental Psychology, 22,* 820-831.

Brown, R. T., & Sleator, E. K. (1979). Methylphenidate in hyperkinetic children: Differences in dose effects on impulsive behavior. *Pediatrics, 64,* 408-411.

Brown, R. T., Slimmer, L. W., & Wynne, M. W. (1984). How much stimulant medication is appropriate for hyperactive children? *Journal of School Health, 54,* 128-130.

Conners, C. K. (1973). Rating scales for use in drug studies in children. *Psychopharmacology Bulletin, Special Issue-Pharmacotherapy in Children,* 24-84.

Coons, H. W., Klorman, R., & Borgstedt, A. D. (1987). Effects of methylphenidate on adolescents with a childhood history of attention deficit disorder: II Information processing. *Journal of the American Academy of Child and Adolescent Psychiatry, 26,* 363-367.

Douglas, V. I. (1984). The psychological processes implicated in ADD. In L. M. Bloomingdale (Ed.), *Attention deficit disorder: Diagnostic, cognitive, and therapeutic understanding* (pp. 147-162). Jamaica, NY Spectrum.

Douglas, V. I., Barr, R. G., Amin, K., O'Neill, M. E., & Britton, B. G. (1988). Dosage effects and individual responsivity to methylphenidate in attention deficit disorder. *Journal of Child Psychology and Psychiatry, 29,* 453-475.

Goyette, C. H., Conners, C. K., & Ulrich, R. F. (1978). Normative data on revised Conners parent and teacher rating scales. *Journal of Abnormal Child Psychology 6,* 221-236.

Gualtieri, C. T., Wargin, W., Kanoy, R., Patrick, K., Shew, C. D., Youngblood, W., Mueller, R. A., & Breese, G. (1982). Clinical studies of methylphenidate serum levels in children and adults peak levels 1-2 hours post ingestion. *Journal of the American Academy of Child Psychiatry, 21,* 19-26.

Jastak, S., & Wilkinson, G. S. (1984). *Manual for the Wide Range Achievement Test (revised).* Wilmington, DE: Jastak.

Kagan, J., Rosman, B., Day, D., Albert, J., & Phillips, W. (1964). Information processing in the child: Significance of analytic and reflective attitudes. *Psychological Monographs, 78* (1. No. 578).

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice-Hall.

Keppel, G. (1982). *Design and analysis* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.

Lambert, N. M., & Sandoval, J. (1980). The prevalence of learning disabilities in a sample of children considered hyperactive. *Journal of Abnormal Child Psychology, 8,* 33-50.

Logan G. D. (1981). Attention, automaticity and the ability to stop a speeded choice response. *Attention and Performance, 9,* 205-222.

Logan, G. D. (1985). Executive control of thought and action. *Acta Psychological, 60,* 193-210.

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review, 91,* 295-327.

Logan, G. D., Cowan, W. B., & Davis, K. A. (1984). On the ability to inhibit simple and choice reaction time responses: A model and a method. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 276-291.

Luce, R. D. (1986). *Response times.* New York: Oxford University Press.

Messer, S. B. (1976). Reflection-impulsivity: A review. *Psychological Bulletin, 83,* 1026-1052.

Milich, R., & Kramer, J. (1984). Reflections on impulsivity: An empirical investigation of impulsivity as a construct. *Advances in Learning and Behavioral Disabilities, 3,* 57-94.

Pelham, W. E., Atkins, M., & Murphy, H. A. (1981, September). ADD with and without hyperactivity: Parent, teacher, and peer rating correlates. In W. E. Pelham (Chair), *DSM-III Category of Attention Deficit Disorder: Rationale, operation, and correlates.* Symposium presented at the annual meeting of the American Psychological Association, Los Angeles.

Peloquin, L. J., & Klorman, R. (1986). Effects of methylphenidate on normal children's mood, event-related potentials, and performance in memory scanning and vigilance. *Journal of Abnormal Psychology, 95,* 88-98.

Rapoport, J., Buchsbaum, M., Zahn, T., Weingartner, H., Ludlow, C., & Mikkelsen, E. (1978). Dextroamphetamine: Cognitive and behavioral effects in normal prepubertal boys. *Science, 199,* 560-563.

Rapport, M. D., Stoner, G., DuPaul, G. J., Kelly, K. L., Tucker, S. B., & Schoeler, T. (1988). Attention deficit disorder and methylphenidate: A multilevel analysis of dose-response effects on children's impulsivity accross settings. *Journal of the American Academy of Child and Adolescent Psychiatry, 27,* 1:60-69.

Rovet, J. (1980). A parametric measure of reflection-impulsivity. *Journal of Applied Developmental Psychology, 1,* 221-225.

Rutter, M., & Graham, P. (1968). The reliability and validity of the psychiatric assessment of the child: I. Interview with the child. *British Journal of Psychiatry, 114,* 563-579.

Rutter, M., Tizard, J., & Whitmore, K. (1970). *Education, health and behavior: Psychological and medical study of childhood development.* New York, Wiley.

Schachar, R., & Logan, G. (1988). *Impulsivity and inhibitory control in normal development and childhood psychopathology.* Manuscript submitted for publication.

Schachar, R., Rutter, M., & Smith, A. (1981). The characteristics of situationally and pervasively hyperactive children: Implications for syndrome definition. *Journal of Child Psychology and Psychiatry, 22,* 375-392.

Schachar, R., & Wachsmuth, R. (1984). *The parent interview for child symptoms.* Unpublished manuscript, Hospital for Sick Children, Department of Psychiatry.

Siegel, L. S., & Heaven, R. K. (1986). Categorization of learning disabilities. In S. J. Ceci (Ed.), *Handbook of cognitive, social, neurological aspects of learning disabilities* (Vol. 1, pp. 95-121). Hillsdale, NJ: Erlbaum.

Solanto, M., & Conners, C. (1982). A dose-response and time-action analysis of autonomic and behavioral effects of methylphenidate in attention deficit disorder with hyperactivity. *Psychophysiology, 19,* 658-667.

Swanson, J., Kinsbourne, M., Roberts, W., & Zucker, K. (1978). Time-response analysis of the effects of stimulant medication on the learning ability of children referred for hyperactivity. *Pediatrics, 61,* 21-29.

Winer, B. J. (1971). *Statistical procedures in experimental design.* New York: McGraw-Hill.

Yando, R. M., & Kagan, J. (1970). The effect of task complexity on reflection-impulsivity. *Cognitive Psychology, 1,* 192-200.