EFFECTS OF METHYLPHENIDATE AND MORPHINE ON DELAY-DISCOUNT FUNCTIONS OBTAINED WITHIN SESSIONS

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Four rats responded under a ''self-control'' procedure designed to obtain delay-discount functions within sessions. Each session consisted of seven blocks, with seven trials within each block. Each block consisted of two initial forced-choice trials followed by five free-choice trials. On choice trials, the rats could press either of two retractable levers. A press on one lever was followed by presentation of a smaller reinforcer (a single dipper presentation of a sucrose solution); a press on the other lever was followed by presentation of a larger reinforcer (four consecutive dipper presentations). The delay associated with the smaller reinforcer always was 0 s, whereas the signaled delay associated with the larger reinforcer increased across blocks (from 0 to 50 s). Under these conditions, the percentage of choices of the larger reinforcer decreased across blocks, and relatively reliable delay-discount functions were obtained within sessions. Doses of methylphenidate (1.0 to 17.0 mg/kg) and morphine (0.3 to 17.0 mg/kg) were then administered prior to selected sessions. Typically, intermediate doses of methylphenidate shifted the discount functions to the right (increased choices of the larger reinforcer). For 2 of the rats, this effect was pronounced; for the other 2 rats, this effect occurred after the range of delays for the larger reinforcer was decreased (0 to 20 s). On the other hand, in most cases morphine produced a slight leftward shift in the discount function (decreased choices of the larger reinforcer). The present procedure appears to be a useful and efficient method to characterize drug effects on an entire delay-discount function. As with many procedures used to study self-control choices, however, sources of control other than reinforcement delay and amount may have been operating in the present study, and these sources must be considered when interpreting drug effects.

Key words: delay discounting, self-control, choice, methylphenidate, morphine, lever press, rats

When experimental subjects are confronted with a choice between a smaller, more immediate reinforcer and a larger, more delayed reinforcer, an individual is said to behave ''impulsively'' when it chooses the former and show ''self-control'' when it chooses the latter (see Logue, 1988). Under these types of conditions (hereafter referred to as ''self-control procedures''), selecting the smaller, more immediate reinforcer apparently results from the diminished effectiveness of the larger reinforcer by the longer delay. Data from a number of studies suggest that the effectiveness of a reinforcer is a decreasing, hyperbolic function of its delay (e.g., Green, Myerson, Holt, Slevin, & Estle, 2004; Mazur, 1987, 1988; Richards, Mitchell, de Wit, & Seiden, 1997). Such ''delay discounting'' appears to represent an important behavioral process. Indeed, several maladaptive behavior patterns have been conceptualized within this framework, including drug abuse, needle sharing by drug users, overeating, procrastination, and attention deficit hyperactivity disorder (ADHD), to name just a few (e.g., Logue, 1995, 2000; Mazur, 1996; Odum, Madden, Badger, & Bickel, 2000; Rachlin, 1974; Simpson & Vuchinich, 2000).

Drugs classified as psychomotor stimulants (e.g., amphetamines and amphetamine-like drugs) are often used therapeutically for impulsive/attentional disorders (e.g.,

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Campbell, Cueva, & Adams, 1999). A number of recent studies have examined the effects of these drugs under self-control procedures in the laboratory. Under conditions most frequently used to study self-control choices (i.e., when the delay to the larger reinforcer is explicitly signaled), stimulants typically increase choices of the larger delayed reinforcer; this has been reported with both nonhumans (e.g., Cardinal, Robbins, & Everitt, 2000; Pitts & Febbo, 2004; Richards, Sabol, & de Wit, 1999; Wade, de Wit, & Richards, 2000) and humans (de Wit, Enggasser, & Richards, 2002; Pietras, Cherek, Lane, Tcheremissine, & Steinberg, 2003). It should be noted that in a few studies, decreases rather than increases in self-control choices following stimulant administration have been obtained (e.g., Charrier & Theibot, 1996; Evenden & Ryan, 1996; Logue, Tobin, Chelonis, Wang, Geary, & Schachter, 1992). The specific variables responsible for these differences across studies have not been elucidated conclusively, but some data indicate that the nature of the stimulus conditions associated with the delay may be important (see Cardinal et al., 2000; also see Pitts & Febbo, 2004 and Richards et al., 1999 for additional discussions of these differences).

Methylphenidate is classified as a mild stimulant with effects generally similar to those of the amphetamines under a variety of conditions (see Hoffman & Lefkowitz, 1996). Despite its frequent use as a treatment for attentional disorders, its effects under laboratory self-control procedures have not been studied nearly as extensively as those of the amphetamines. To our knowledge, there are no published reports of the effects of methylphenidate on self-control choices in nonhuman animals. Pietras et al. (2003) examined effects of methylphenidate on delay-discounting in adult humans with a history of criminal behavior. They reported that methylphenidate increased choices of a larger, more delayed reinforcer (points that were exchanged for money at the end of each session) in 7 of 11 subjects.

In addition to the data with methylphenidate reported by Pietras et al. (2003), and the data with other psychomotor stimulants reviewed above, there are other reasons to suspect that methylphenidate might increase self-control choices in nonhumans. Sagvolden, Slatta, and Arntzen (1988) arranged conditions in which rats' nose pokes to a target hole within a 4 × 5 array of holes were reinforced according to a fixed-interval (FI) schedule. Under nondrug conditions, nose poking showed a typical scalloped pattern. Furthermore, the proportion of pokes to the target and adjacent locations was an increasing function of time in the FI. Administration of lower doses of methylphenidate produced an increase in the proportion of pokes to the target and adjacent locations during the early portion of the FI. Although there are several potential interpretations, Sagvolden et al. suggested that the methylphenidate-induced change in the spatio-temporal distribution of nose pokes might reflect an altered delay-of-reinforcement gradient. That is, they suggested that methylphenidate attenuated the effects of reinforcement delay on responses early in the FI. Indeed, although there are a variety of interpretations (e.g., Dews & Wenger, 1977; Meck, 1983), the characteristic increase in response rates early in the inter-reinforcement interval under traditional FI schedules of reinforcement following administration of psychomotor stimulants can be viewed as an attenuation of the effects of reinforcement delay.

The purpose of the present study was to examine effects of methylphenidate on choice under a self-control procedure with rats. In an attempt to characterize methylphenidate's effects on the function relating choice to delay, a procedure similar to that used by Evenden and Ryan (e.g., 1996, 1999) was employed. These investigators used a within-session procedure in which the delay to a larger reinforcer escalates across blocks of choice trials. This procedure provides an efficient method for examining drug effects on the entire delay-discount function. In the present study, rats were given repeated choices between a larger reinforcer and a smaller, immediate reinforcer. Each session began with the delay to the larger reinforcer set equal to that of the smaller reinforcer (0 s). The signaled delay to the larger reinforcer was manipulated across blocks of trials such that a delay-discount function was obtained within each session. After stable daily discount functions were established, effects of various doses of methylphenidate were examined.

For comparison, effects of the μ-opiate agonist morphine also were assessed. It was reported recently that this drug decreased self-control choices in rats responding under an adjusting-amount procedure (Kieres, Hausknecht, Farrar, Acheson, de Wit, & Richards, 2004). Thus the present study provided an assessment of the reliability and generality of those findings, along with information about the effects of morphine on the shape of the entire discount function.

METHOD

Subjects

Four male Holtzman Sprague-Dawley rats (P1, P2, P3, and P4), between 90 and 120 days old at the start of the study, served as subjects. The rats were housed individually in a colony room and were maintained under a regimen of food and water restriction. This regimen involved providing access to food and water for 1 hr, beginning approximately 30 min after each session (or at the corresponding time on days in which sessions were not conducted). This resulted in approximately 21 hr of food and water deprivation prior to each experimental session. Under this regimen, the rats' weights ranged from approximately 350 to 450 g.

Apparatus

Two identical Lehigh Valley Electronics modular operant-conditioning chambers (model #E10-10SF, 29.0 cm long, 25.0 cm wide, and 29.0 cm high) were contained within sound-attenuating enclosures. The front and back walls and the ceiling of each chamber were made of stainless steel, and the side walls were made of Plexiglas. The front wall of each chamber contained a 28-V DC houselight (#1820 bulb), two retractable levers (Med Associates® model #ENV112BM), two 28-V DC stimulus lamps (#1820 bulbs, each covered by a white lens cap), and a 3.0 by 4.0 cm opening into which a dipper cup could be raised. The houselight was centered 3.0 cm below the ceiling. Each lever was located 7.0 cm from the grid floor, with the edge 1.0 cm from its respective side wall. Each stimulus lamp was located 7.0 cm directly above its corresponding lever, and the dipper opening was centered 4.0 cm from the floor. When the dipper was raised, the cup contained a 0.02 cc drop of a 15% (w/v) solution of sucrose in water, a 28 V DC lamp illuminated the opening, all other lights in the chamber were extinguished, and the levers were retracted. Each dipper presentation provided 3-s access to the sucrose solution. When extended, each lever required a downward force of approximately 0.25 N to operate; lever extension/retraction required approximately 1.0 s.

Continuous white noise was present in the surrounding room and within each enclosure to mask extraneous sounds, and each enclosure was equipped with a ventilation fan that provided air circulation within the experimental space. Experimental events were programmed and data were recorded from an adjoining room by an MS-DOS-controlled 80486 microcomputer using Med Associates® (Georgia, VT) software and interface equipment operating at 0.01-s resolution.

Procedure

Preliminary training. Following adaptation to the chamber (two 30-min sessions) and magazine training, lever pressing was shaped by differentially reinforcing successive approximations. Initially, 2 rats (P1 and P2) were trained to press the right lever and 2 rats (P3 and P4) were trained to press the left lever. During these sessions, the houselight was illuminated, the active lever was extended, and the lamp above it was illuminated. After shaping, each response was reinforced (fixed-ratio [FR] 1) for two sessions; responses on the initially active lever were reinforced during the first session and responses on the other lever were reinforced during the second session. In each of these sessions, the inactive lever was retracted and the lamp above it was off. These sessions terminated following the 30th dipper presentation. Next, lever pressing was reinforced under a multiple FR 1 FR 1 schedule. In one component, the left lever was extended and in the other component, the right lever was extended. For Rats P1 and P4, while the right lever was extended, the lamp above it blinked (0.3 s on, 0.3 s off) and while the left lever was extended, the lamp above it was continuously illuminated; for Rats P2 and P3, this relation was reversed. Each press on the lever below the blinking lamp retracted the lever and produced four consecutive presentations

of the dipper, each separated by 0.5 s (the larger reinforcer). Each press of the lever below the continuously illuminated lamp retracted the lever and produced one presentation of the dipper (the smaller reinforcer). Each exposure to a component lasted for one reinforcer, and each reinforcer delivery was followed by a 5-s blackout, during which both levers were retracted. Sessions ended after 42 reinforcer deliveries (21 of each type). The order of exposure to the components within each session was semirandom with the restriction that no component could be presented for more than three consecutive reinforcers.

After 10 sessions, a discrete-trials choice procedure was implemented. Each session consisted of 42 trials and each trial began with the illumination of the houselight. After 2 s, both levers extended, and the lights above them were illuminated (one blinking and one continuously). The contingencies associated with each lever were the same as those described above; pressing one lever (below the blinking lamp) produced the larger reinforcer and pressing the other lever (below the continuously illuminated lamp) produced the smaller reinforcer. Each lever press retracted both levers and resulted in an immediate presentation of the corresponding reinforcer. Trials were separated by 60-s intertrial intervals (ITIs), during which all lights were extinguished and the levers retracted. For each of the rats, this procedure remained in effect until an exclusive preference for the larger reinforcer occurred for at least five consecutive sessions; this required between 21 and 27 sessions.

Experimental procedure. During the remainder of the study, the delay to the larger reinforcer was manipulated within each session. Each session lasted 49 trials or 90 min, whichever occurred first. The events comprising the trials were similar to those described above: the houselight illuminated for 2 s, followed by lever extension and illumination of the corresponding lever lamp(s). The 49-trial sessions were divided into seven blocks of seven trials each. During the first block of each session, the contingencies were exactly as those described above; the rats chose between the immediate larger reinforcer and the immediate smaller reinforcer. The delay to the larger reinforcer was increased across the remaining blocks while the contingencies associated with the smaller reinforcer remained the same. Under these conditions, each choice of the larger reinforcer initiated a signaled delay. During the delay, the houselight and the lamp above the other lever were extinguished, both levers were retracted, and the lamp above the lever associated with the larger reinforcer continued to blink. At the termination of the delay, the blinking lamp was extinguished and the larger reinforcer was delivered.

For each block, the first two trials were forced trials, one of each choice type, in which only one of the levers was extended and the contingencies associated with pressing that lever for that block were in effect. That is, for each block, the forced trial involving the larger reinforcer arranged the delay value in effect for the remaining choice trials of that block. The order of the forced trials across blocks was semirandomly determined with the restriction that no trial type could appear first for more than three consecutive blocks. The remaining five trials of each block were choice trials. Trials were separated by ITIs. Within blocks, each trial was presented 90 s following the choice response of the previous trial. Thus the duration of each ITI was 90 s minus delay and reinforcement time. The ITIs between blocks were longer than those between trials within a block; the first trial of each block was presented 120 s following the choice response on the last trial of the previous block. With this arrangement, the rate at which trials occurred was unaffected by choice (i.e., choosing the smaller reinforcer did not increase the rate at which the rats could choose). Thus ITIs following choices of the larger reinforcer were shorter than those following choices of the smaller reinforcer.

Initially, different sequences of larger reinforcer delays were implemented, each for several sessions, in hopes of achieving a sensitive baseline against which to assess effects of drugs. The sequence of delay values used during drug testing was 0, 5, 10, 20, 30, 40, and 50 s. These values were arrived at by examining daily functions for each rat (see *Data Analysis*) and selecting those that produced a pattern of choice most closely resembling an exclusive preference for the larger reinforcer for the first block or two, followed by a transition to an exclusive

preference for the smaller reinforcer over the last two or three blocks. Following determination of dose-effect functions at these values, the sequence of delays for Rats P2 and P4 was changed to 0, 2, 4, 8, 12, 16, and 20 s and the dose-effect functions for methylphenidate were redetermined (see *Pharmacological procedure*).

Once or twice per week (on Monday, Tuesday, and/or Wednesday), a no-delay control procedure was conducted in which the larger reinforcer was presented immediately (0-s delay) in all blocks. These sessions provided an indication of the degree to which the choice pattern in a given session was controlled by the currently programmed delays rather than (or in addition to) other variables (e.g., a particular choice history). On rare occasions, a subject (usually Rat P4) chose the smaller reinforcer on several trials during a no-delay control session. When this occurred, the next scheduled injection was cancelled and additional no-delay control sessions were conducted until a substantial preference for the larger reinforcer during these conditions was recovered.

Sessions were conducted 5 days per week (Monday through Friday). Once choice patterns under the experimental procedure appeared consistent for 10 consecutive sessions, as determined by inspection of daily discount functions, drug testing was implemented. The number of baseline sessions conducted at the 0- to 50-s delay sequence prior to the initiation of drug testing was 88 (13 of which were no-delay control sessions), 99 (22), 87 (13), and 98 (23) for Rats P1, P2, P3, and P4, respectively.

Pharmacological procedure. Methylphenidate hydrochloride (Sigma) and morphine sulfate (from the National Institute on Drug Abuse; generously donated by Dr. Mark Galizio) were dissolved in 0.9% sodium chloride (saline) and injected *i.p.* in a volume of 1.0 ml/kg. Saline, methylphenidate (1.0 to 17.0 mg/kg), or morphine (0.3 to 17.0 mg/kg) was injected 15 min prior to selected sessions. Doses are expressed in terms of the salt forms listed above. Injections always occurred on Fridays, with the data from the preceding Thursday serving as a no-injection control. A scheduled injection was cancelled if the data from its no-injection control appeared atypical (as determined by inspection of the discount functions). Methylphenidate was tested first (all 4 rats), followed by morphine (Rats P1, P2, and P3). The delay values for Rats P2 and P4 then were altered and, after stable performance was reestablished, effects of several doses of methylphenidate were redetermined. A 2-week period without injection intervened between termination of testing with one drug and initiation of testing with another; scheduled experimental sessions continued during this period. Effects of each dose and saline were determined at least twice, and in some cases three or four times (when effects of the first two determinations were discrepant). Doses were tested in an irregular order with the restriction that no dose was tested a second time before all doses had been tested once. Because of their advanced ages, redetermination of the methylphenidate dose-effect function at the altered delay values for Rats P2 and P4 involved a single determination of selected doses.

Data Analysis

The primary dependent measure was the number of larger reinforcer choices per block (maximum value = 5). For each session, a *discount function* for each rat was obtained by plotting the number of larger reinforcer choices as a function of its delay; for the no-delay control sessions, the number of large reinforcer choices was plotted as a function of block. Drug effects were characterized by averaging the discount functions across sessions for no-injection control conditions, for sessions following saline injections (''saline sessions''), and for sessions following injection of each drug dose. Whenever a session ended via the time limit, the analysis included all trials up through the last completed block (i.e., trials from incomplete blocks were excluded).

To characterize dose-effect functions, a single measure for each session was obtained. This measure, referred to as the *delay of indifference*, served as an estimate of the delay value at which both options would be chosen equally. The delay of indifference was obtained by finding the two delay values adjacent to the point at which the function crossed 2.5 (the midpoint on the *y* axis), and then estimating that point by interpolation. Finally, overall response latency was collected on both forced and choice trials (defined as

the time between extension of the lever(s) and the subsequent press). These data were converted to *overall response speed* (1/latency). If a session ended via the time limit and the latency timer was running (i.e., if the session ended while the levers were extended), the time was included in the denominator of the speed calculation. Session averages for delay of indifference and response speed were obtained under no-injection control conditions and following administration of each dose and saline. Dose-effect functions for each drug were expressed as a percentage of data obtained during the corresponding saline sessions (''percent saline''), in which the average effect of each dose was divided by the average effect of saline and the result multiplied by 100.

RESULTS

Control Performance

Figure 1 shows discount functions for each rat under no-injection control conditions

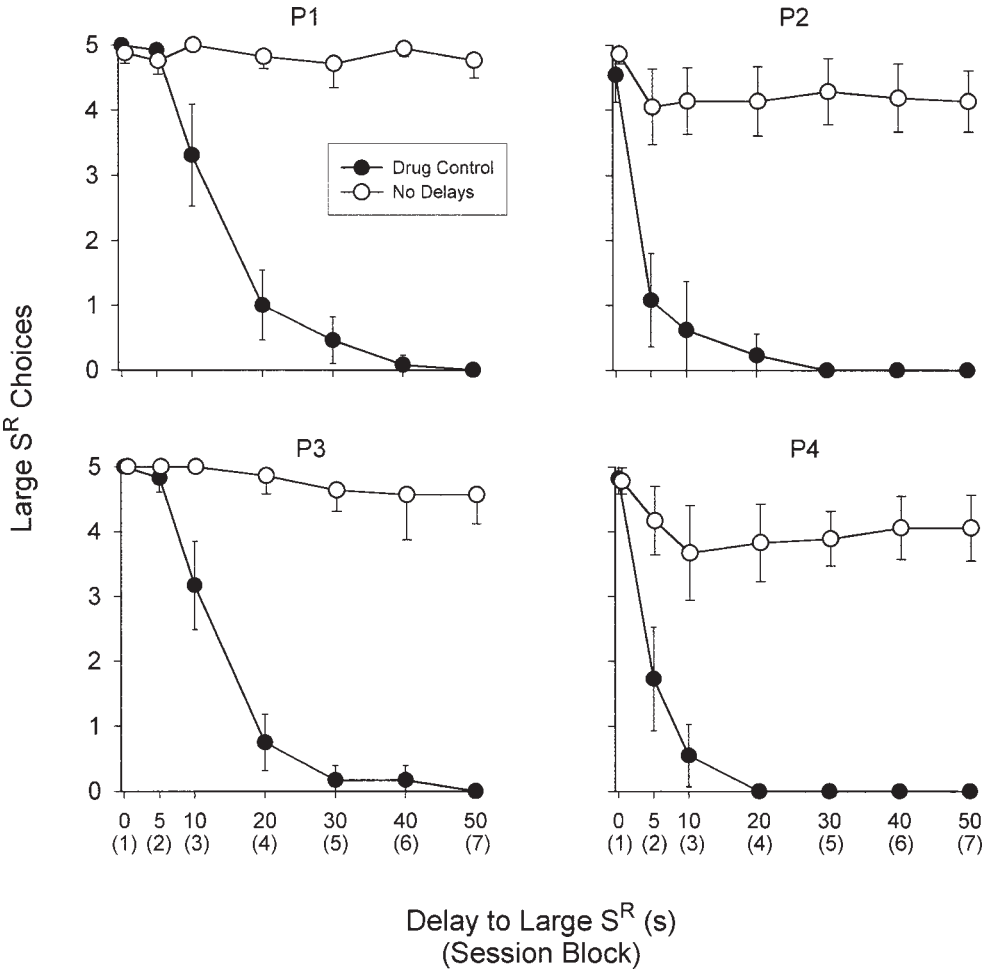

Fig. 1. Number of larger reinforcer choices by individual rats as a function of delay, or block. Filled symbols show means from all no-injection control sessions (''Drug Control'') during determination of the effects of methylphenidate (n = 12 for Rats P1, P2, and P3; n = 11 for Rat P4); unfilled symbols show means from all no-delay control sessions (''No Delays'') during determination of the effects of methylphenidate (n = 13 for Rat P1; n = 12 for Rats P2 and P3; n = 11 for Rat P4). Error bars show 95% confidence intervals. Absence of an error bar indicates that the confidence intervals fell within the area covered by the symbol. For Rat P2, the means at the 30-, 40-, and 50-s delays were obtained from fewer values than other means in the function as this rat occasionally failed to complete all blocks of the session (i.e., the session ended via the time limit). Only data from completed blocks were included in the analysis.

(filled circles). During the first block, when the delay for both reinforcers was 0 s, each rat chose the larger reinforcer nearly exclusively. As its delay increased, the likelihood of choosing the larger reinforcer decreased for all rats. Once the delay reached 30 s, all rats chose the smaller reinforcer nearly exclusively. The discount functions for Rats P2 and P4 were steeper than those for P1 and P3. For Rats P1 and P3, a delay of 20 s was required to shift preference from the larger to the smaller reinforcer, whereas for P2 and P4, nearly exclusive preference for the smaller reinforcer occurred at the 10-s delay. Note that Rat P2 often was slow to respond and, thus, sessions occasionally ended via the time limit (see Figure 4). Typically, administration of saline had no effect on choice (see Figures 2 and 3).

Figure 1 also shows performance under no-delay control conditions (unfilled circles), in which the delays for both the larger and smaller reinforcer were 0 s across all blocks. For all rats under these conditions, choices of the larger reinforcer substantially exceeded those of the smaller reinforcer for all of the blocks. For 3 of the 4 rats (P1 was the exception), the likelihood of choosing the larger reinforcer was slightly lower in the later blocks than in the earlier blocks; this was most prevalent with Rat P4. Note that Rat P2 completed all of the sessions under the no-delay control condition.

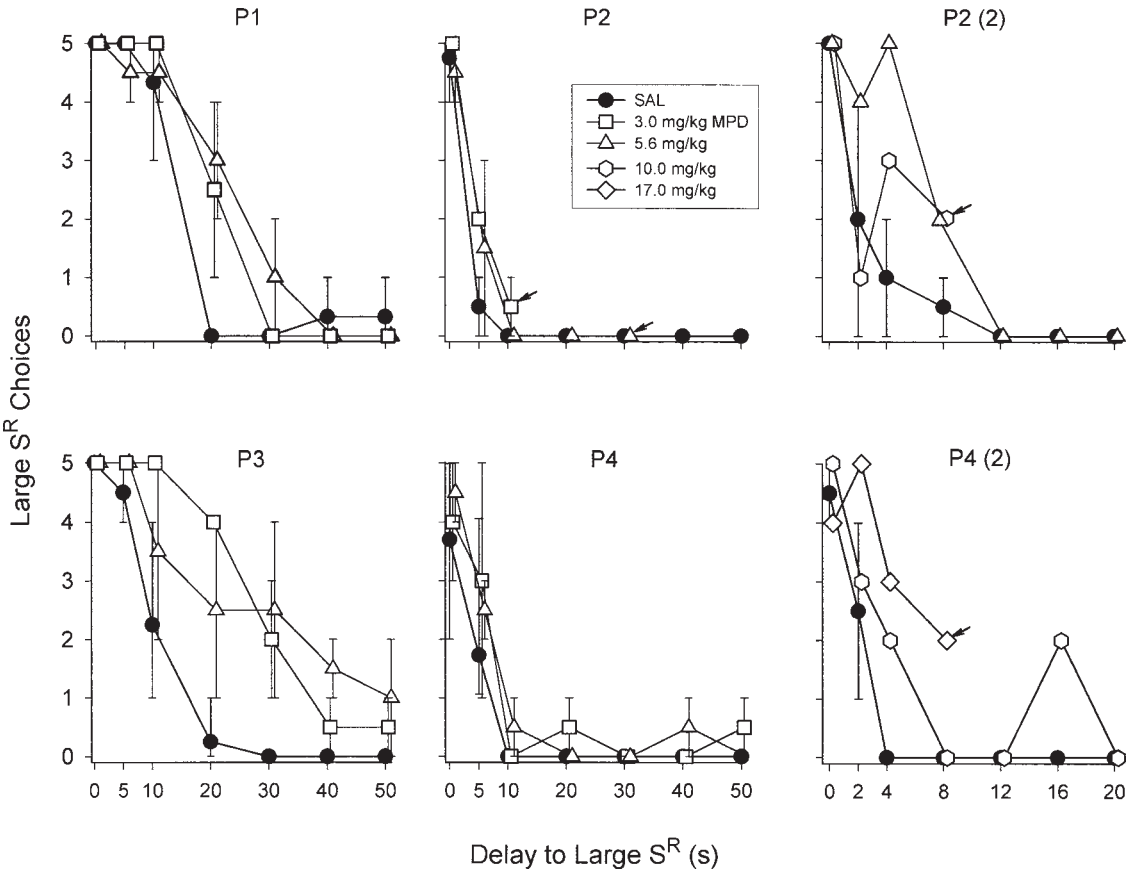

Fig. 2. Effects of selected doses of methylphenidate (MPD) on the discount functions for individual rats. Data in the center column for Rats P2 and P4 are from sessions with the original delay sequence, and data in the right column for these rats are from sessions with the altered delay sequence. Filled symbols show means from two to four determinations of the effects of saline; unfilled symbols in the left and center columns show means from two to three determinations of the indicated dose; unfilled symbols in the right column show effects of a single determination (note that a range for saline is shown in Rat P4(2)—this rat received saline twice under these conditions). Partial functions (e.g., Rat P4(2) at 17.0 mg/kg), noted by arrows, indicate that the rat did not complete the session(s) under this condition (i.e., sessions ended via the time limit); only data from completed blocks were included in the analysis. Error bars show ranges.

Table 1

Mean number of choices of the larger reinforcer for each rat at each delay for control sessions, saline sessions, and at each dose of methylphenidate under the original delay sequence (MPD1) and under the altered delay sequence (MPD2). Numbers in parentheses next to each condition label indicate the number of observations, and numbers in parentheses beside each mean value indicate ranges.

	Delay to large reinforcer (s)						
Rat P1	0	5	10	20	30	40	50
Control (12)	5.00 (5–5)	4.92 (4–5)	3.31 (2–5)	0.83 (0–2)	0.47 (0–2)	0.08 (0–1)	0.00 (0–0)
Sal (3)	5.00 (5–5)	5.00 (5–5)	4.33 (3–5)	0.00 (0–0)	0.00 (0–0)	0.33 (0–1)	0.67 (0–1)
1.0 mg/kg (2)	5.00 (5–5)	5.00 (5–5)	3.00 (2–4)	1.50 (1–2)	0.50 (0–1)	0.00 (0–0)	0.00 (0–0)
3.0 mg/kg (2)	5.00 (5–5)	5.00 (5–5)	5.00 (5–5)	2.50 (1–4)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
5.6 mg/kg (2)	5.00 (5–5)	4.50 (4–5)	4.50 (4–5)	3.00 (2–4)	1.00 (0–2)	0.00 (0–0)	0.00 (0–0)
10.0 mg/kg (3)	5.00 (5–5)	5.00 (5–5)	3.67 (2–5)	2.33 (2–3)	0.67 (0–2)	0.67 (0–1)	0.50 (0–1)[a]
Rat P2							
MPD 1	0	5	10	20	30	40	50
Control (12)	4.54 (3–5)	1.08 (0–3)	0.62 (0–1)	0.23 (0–1)	0.00 (0–0)[a]	0.00 (0–0)[a]	0.00 (0–0)[a]
Sal (4)	4.75 (4–5)	0.50 (0–1)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)[a]	0.00 (0–0)[a]	0.00 (0–0)[a]
1.0 mg/kg (2)	4.50 (4–5)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00[a]	0.00[a]
3.0 mg/kg (2)	5.00 (5–5)	2.00 (2–2)	0.50 (0–1)	–[b]	–[b]	–[b]	–[b]
5.6 mg/kg (2)	4.50 (4–5)	1.50 (0–3)	0.00 (0–0)	0.00[a]	0.00[a]	–[b]	–[b]
10.0 mg/kg (1)	5.00	2.00	–[b]	–[b]	–[b]	–[b]	–[b]
MPD 2	0	2	4	8	12	16	20
Control (5)	5.00 (5–5)	2.20 (1–5)	1.00 (0–3)	0.40 (0–1)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
Sal (1)	5.00	3.00	1.00	0.00	0.00	0.00	0.00
1.0 mg/kg (1)	5.00	5.00	1.00	1.00	0.00	0.00	0.00
3.0 mg/kg (1)	5.00	2.00	1.00	0.00	0.00	0.00	1.00
5.6 mg/kg (1)	5.00	4.00	5.00	2.00	0.00	0.00	0.00
10.0 mg/kg (1)	5.00	1.00	3.00	2.00	–[b]	–[b]	–[b]
Rat P3	0	5	10	20	30	40	50
Control (12)	5.00 (5–5)	4.83 (4–5)	3.17 (1–5)	0.75 (0–2)	0.17 (0–1)	0.17 (0–1)	0.00 (0–0)
Sal (4)	5.00 (5–5)	4.50 (4–5)	2.25 (1–4)	0.25 (0–1)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
1.0 mg/kg (2)	5.00 (5–5)	5.00 (5–5)	5.00 (5–5)	0.00 (0–0)	0.00 (0–0)	0.50 (0–1)	0.50 (0–1)
3.0 mg/kg (2)	5.00 (5–5)	5.00 (5–5)	5.00 (5–5)	4.0 (4–4)	2.00 (1–3)	0.50 (0–1)	0.50 (0–1)
5.6 mg/kg (2)	5.00 (5–5)	5.00 (5–5)	3.50 (2–5)	2.50 (1–4)	2.50 (1–4)	1.50 (1–2)	1.50 (1–2)
10.0 mg/kg (2)	4.50 (4–5)	4.50 (4–5)	1.00 (1–1)	0.00[a]	–[b]	–[b]	–[b]
Rat P4							
MPD 1	0	5	10	20	30	40	50
Control (11)	4.82 (4–5)	1.73 (0–4)	0.55 (0–2)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
Sal (2)	4.50 (4–5)	1.67 (1–4)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
1.0 mg/kg (2)	4.00 (3–5)	1.00 (0–2)	0.00 (0–0)	0.00 (0–0)	0.50 (0–1)	0.00 (0–0)	0.00 (0–0)
3.0 mg/kg (2)	4.00 (3–5)	3.00 (1–5)	0.00 (0–0)	0.50 (0–1)	0.00 (0–0)	0.00 (0–0)	0.50 (0–1)
5.6 mg/kg (2)	4.50 (4–5)	2.50 (2–3)	0.50 (0–1)	0.00 (0–0)	0.00 (0–0)	0.50 (0–1)	0.00 (0–0)
10.0 mg/kg (2)	4.50 (4–5)	2.00 (1–3)	0.50 (0–1)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
MPD 2	0	2	4	8	12	16	20
Control (7)	4.43 (3–5)	2.00 (0–4)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.14 (0–1)	0.00 (0–0)
Sal (2)	3.50 (3–4)	0.50 (0–1)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
1.0 mg/kg (1)	5.00	1.00	0.00	0.00	0.00	0.00	0.00
3.0 mg/kg (1)	5.00	1.00	0.00	0.00	0.00	0.00	0.00
5.6 mg/kg (1)	3.00	1.00	0.00	0.00	0.00	0.00	0.00
10.0 mg/kg (1)	5.00	3.00	2.00	0.00	0.00	2.00	0.00
17.0 mg/kg (1)	4.00	5.00	3.00	2.00	–[b]	–[b]	–[b]

[a] did not finish this block in a subset of sessions; data presented only for sessions in which block was completed.
[b] did not finish this block in any of the sessions.

Effects of Methylphenidate

Figure 2 shows effects of selected methylphenidate doses on the discount functions of each rat, compared with performance following saline administration (filled circles). The doses selected were those that produced the largest effects on choice; lower doses produced little or no effect on choice and higher doses tended to suppress responding substantially (see Figures 3 and 4). Table 1 shows data for no-injection and saline control conditions and for all of the methylphenidate doses. For Rats

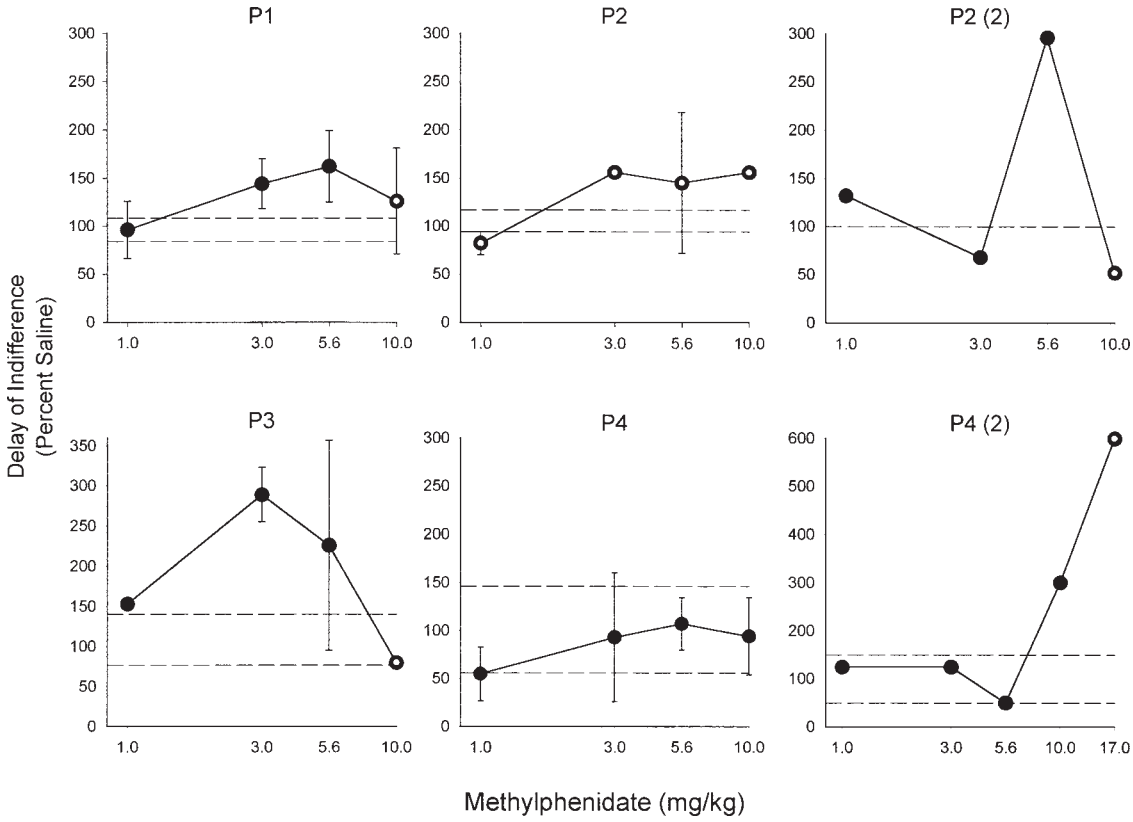

Fig. 3. Dose-effect functions for methylphenidate on the delay of indifference (see text for a description of this measure), plotted as a percentage of data obtained from saline sessions. Dashed lines indicate the range of effects of saline; upper and lower lines show the results of taking the highest and lowest values, respectively, dividing those by the mean value and multiplying the result by 100. Note that the *y* axes differ across rats. A white dot within a symbol indicates that some of the data were obtained from sessions that ended via the time limit (only data from completed blocks were included). Vertical lines show ranges. The absence of a vertical line indicates that the range fell within that covered by the data point. Note that data in the right panels for Rats P2 and P4, and for 10.0 mg/kg in the center panel for Rat P2, were from a single determination (except that saline was given twice to Rat P4 at the altered delay sequence).

P1 and P3 (left panels), both 3.0 and 5.6 mg/kg clearly shifted the discount function to the right. That is, at these doses, Rats P1 and P3 selected the larger reinforcer at longer delays than under saline. For example, following saline administration, a delay of 20 s produced exclusive or nearly exclusive selection of the smaller reinforcer. At both 3.0 and 5.6 mg/kg, however, both of these rats chose the larger reinforcer on 50% or more of the trials. Note that for both of these rats, 5.6 mg/kg produced a larger effect than 3.0 mg/kg at the longer delays, whereas at the shorter delays, the reverse was the case.

For Rats P2 and P4 at the original delay values (middle panels of Figure 2), 3.0 and 5.6 mg/kg slightly increased choice of the larger reinforcer at the 5-s delay and, for Rat P4, at some of the longer delays. None of the doses, however, shifted the discount function appreciably in these rats. Note that Rat P2 did not finish the sessions at either dose (see response speed data in Figure 4).

Altering the delays modified the effects of methylphenidate on the delay-discount functions for Rats P2 and P4 (right panels of Figure 2; also see Table 1). Under the altered delay sequence, the effects of methylphenidate for Rats P2 and P4 were comparable to those obtained with P1 and P3 under the original delay sequence; for Rats P2 and P4, however, slightly higher doses were required to achieve this effect. For Rat P2, 5.6 mg/kg produced a substantial rightward shift in the function,

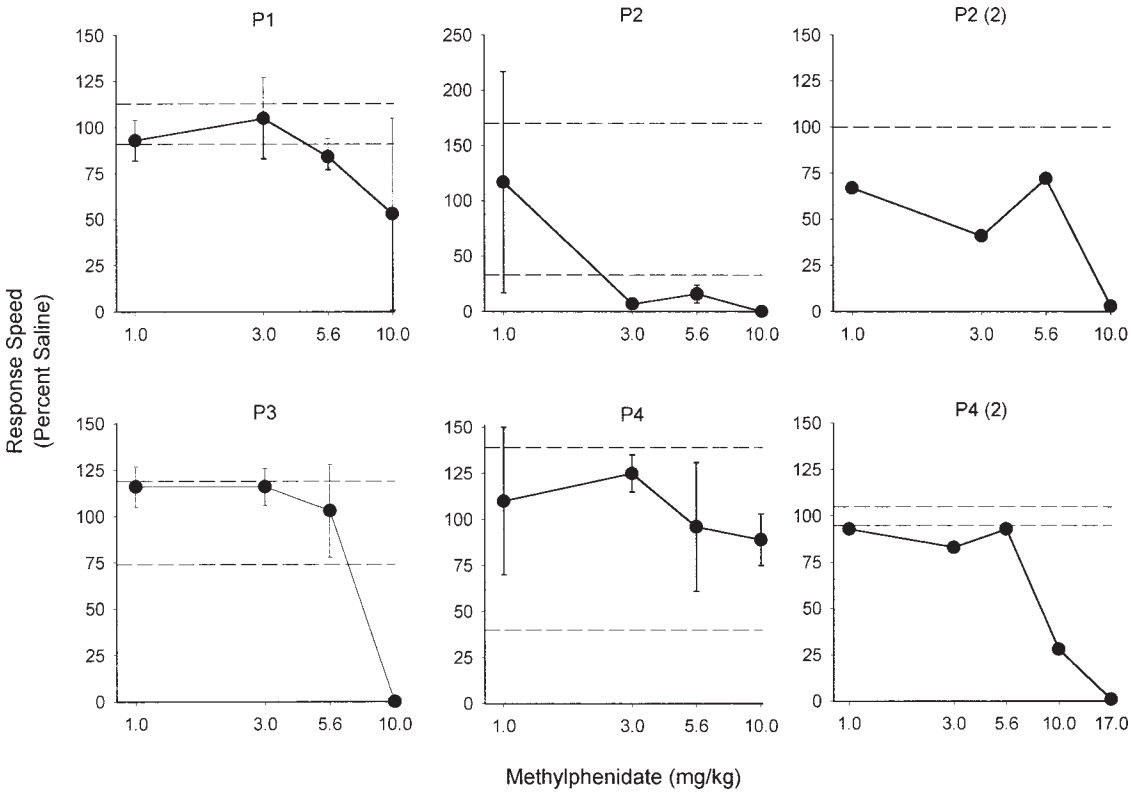

Fig. 4. Dose-effect functions for methylphenidate on response speed (see text for a description of this measure), plotted as a percentage of data obtained from saline sessions. Note that the *y* axes differ across rats. All other characteristics of this figure are as described in the caption of Figure 3.

whereas this dose had only a slight effect at the original delays (other than to reduce response speed; see Figure 4). At this dose, Rat P2 finished the session under the altered delays, but not under the original delays. At 10.0 mg/kg, the number of larger reinforcer choices was increased for Rat P2 at delays of 4 and 8 s, although this rat did not finish the session. For Rat P4, 10.0 mg/kg shifted the entire function to the right and 17.0 mg/kg increased choices of the larger reinforcer at the 2-, 4-, 8-, and 12-s delays, although the session ended via the time limit at the higher dose. It should be noted that, under nondrug conditions, the effects of delay on choice were more pronounced at the altered delay sequence, particularly for Rat P4. That is, the actual delay at which choice shifted to the smaller reinforcer was shorter under the altered delay sequence.

Figure 3 shows dose-effect functions for methylphenidate on the delay of indifference (percent saline). These data corroborate those shown in Figure 2. Following administration of saline, the average delay of indifference was higher for Rats P1 and P3 (13.89 and 9.79 s, respectively) than for Rats P2 and P4 (2.66 and 4.69 s, respectively). For Rats P1 and P3, both 3.0 and 5.6 mg/kg increased this measure, although for Rat P3 the effect of 5.6 mg/kg was somewhat inconsistent. For Rat P1, the largest increase occurred at 5.6 mg/kg (from 13.89 to 22.50 s, or more than 150% of saline), whereas for Rat P3, the largest increase occurred at 3.0 mg/kg (from 9.79 s to 28.34 s, or more than 250% of saline). For Rat P2 at the original delays, 3.0, 5.6, and 10.0 mg/kg all increased delay of indifference to approximately 150% of saline. Note, however, that, because the delay of indifference at saline for this rat was relatively short (2.66 s), this effect represents a small absolute change (to between 3.85 and 4.16 s). None of the doses affected the delay of indifference for Rat P4 at the original delays. In contrast, the right panels of Figure 3 show that for both Rats P2 and P4 under the altered delay sequence, the

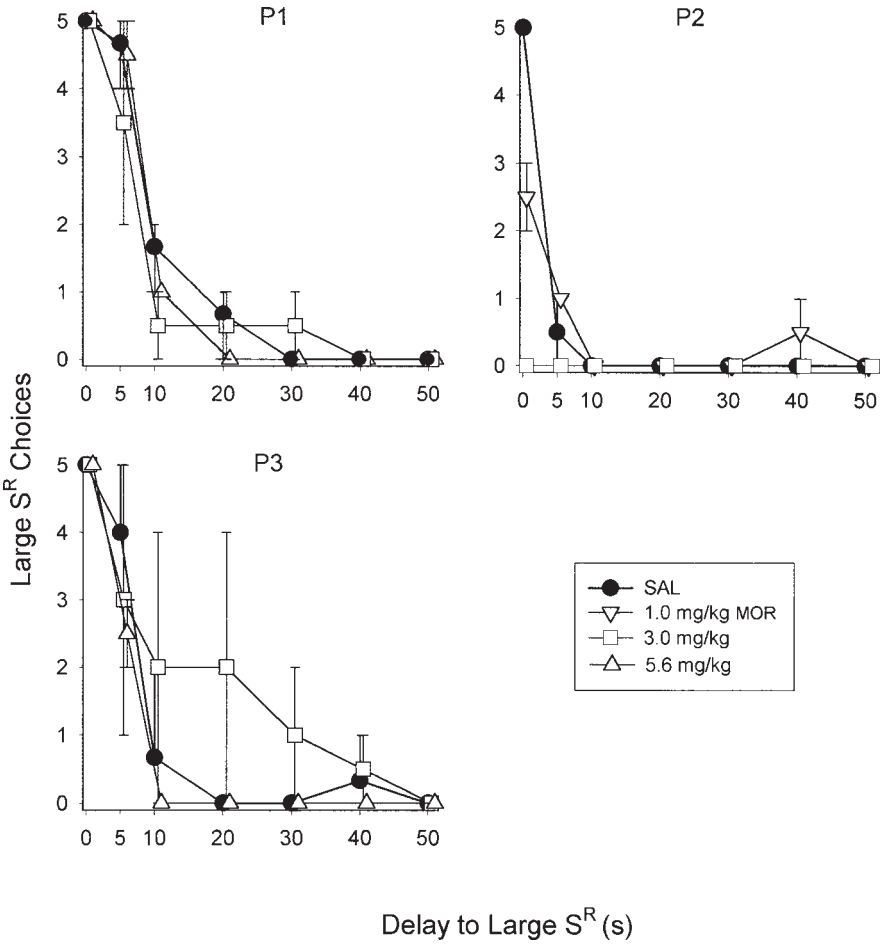

Fig. 5. Effects of selected doses of morphine (MOR) on the discount functions for Rats P1, P2, and P3. All other characteristics of this figure are as described in the caption of Figure 2.

delay of indifference was substantially increased by at least one dose (5.6 mg/kg for Rat P2, and 10.0 and 17.0 mg/kg for Rat P4). For both rats, particularly P4, the delay of indifference measure under saline was slightly lower at the altered delay sequence than at the original sequence.

Figure 4 shows methylphenidate dose-effect functions for response speed (percentage saline). For the most part, this drug produced dose-related decreases in this measure. For Rats P1 and P3 (left panels), response speed was decreased at the highest dose (10.0 mg/kg), but was unaffected by doses that increased the delay of indifference (3.0 and 5.6 mg/kg). For Rats P2 and P4, response speed during saline sessions was highly variable at the original delays (middle panels). Rat P2 sometimes did not finish the session, even under nondrug conditions, and responding was nearly completely suppressed at doses above 1.0 mg/kg. In contrast, none of the doses affected response speed for Rat P4 at the original delays. When the delay sequence was altered (right panels), response speed for Rat P2 increased under nondrug conditions (this rat reliably finished each session) and was less sensitive to the effects of methylphenidate. For Rat P4, this measure was less variable under the altered delay sequence than under the original sequence. Note that under the altered delays, the methylphenidate-induced shifts in the discount functions for both Rats P2 (at 5.6 mg/kg) and P4 (at 10.0 mg/kg) were accompanied by decreases in response speed.

Table 2

Mean number of choices of the larger reinforcer during determination of the morphine dose-effect curve. All characteristics of this table are identical to those described for Table 1.

	Delay to large reinforcer (s)						
Rat P1	0	5	10	20	30	40	50
Control (13)	4.85 (4–5)	4.69 (3–5)	2.92 (0–5)	1.23 (1–3)	0.08 (0–1)	0.00 (0–0)	0.08 (0–1)
Sal (3)	5.00 (5–5)	4.67 (4–5)	1.67 (1–2)	0.67 (0–1)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
1.0 mg/kg (2)	5.00 (5–5)	5.00 (5–5)	2.50 (2–3)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
3.0 mg/kg (2)	5.00 (5–5)	3.50 (2–5)	0.50 (0–1)	0.50 (0–1)	0.50 (0–1)	0.00 (0–0)	0.00 (0–0)
5.6 mg/kg (2)	5.00 (5–5)	4.50 (4–5)	1.00 (1–1)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
10.0 mg/kg (2)	5.00 (5–5)	3.50 (3–4)	0.50 (0–1)	0.00 (0–0)	0.50 (0–1)	0.00 (0–0)	0.50 (0–1)
17.0 mg/kg (2)	5.00 (5–5)	1.50 (1–2)	1.00[a]	0.00[a]	0.00[a]	–[b]	–[b]
Rat P2							
Control (9)	4.40 (3–5)	0.80 (0–2)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)[a]	0.00 (0–0)[a]
Sal (2)	5.00 (5–5)	0.50 (0–1)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
0.3 mg/kg (2)	4.00 (3–5)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)[a]
1.0 mg/kg (2)	2.50 (2–3)	1.00 (1–1)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.50 (0–1)	0.00 (0–0)
3.0 mg/kg (2)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00[a]	0.00[a]	0.00[a]	0.00[a]
5.6 mg/kg (1)	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]
Rat P3							
Control (12)	5.00 (5–5)	4.50 (4–5)	1.42 (0–3)	0.17 (0–1)	0.08 (0–1)	0.08 (0–1)	0.17 (0–1)
Sal (3)	5.00 (5–5)	4.00 (3–5)	0.67 (0–2)	0.00 (0–0)	0.00 (0–0)	0.33 (0–1)	0.00 (0–0)
1.0 mg/kg (2)	5.00 (5–5)	5.00 (5–5)	3.00 (3–3)	0.50 (0–1)	1.00 (1–1)	0.00 (0–0)	0.00 (0–0)
3.0 mg/kg (2)	5.00 (5–5)	3.00 (1–5)	2.00 (0–4)	2.00 (0–4)	1.00 (0–2)	0.50 (0–1)	0.00 (0–0)
5.6 mg/kg (2)	5.00 (5–5)	2.50 (2–3)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)	0.00 (0–0)
10.0 mg/kg (2)	5.00 (5–5)	2.50 (2–3)	1.00 (0–2)	0.00 (0–0)	0.00[a]	0.00[a]	0.00[a]
17.0 mg/kg (1)	4.00	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]

[a] did not finish this block in a subset of sessions; data presented only for sessions in which block was completed.
[b] did not finish this block in any of the sessions.

Effects of Morphine

Figure 5 shows effects of selected morphine doses on the discount functions for Rats P1, P2, and P3 (Table 2 contains data for all doses). With the exception of Rat P3 at 3.0 mg/kg, these doses of morphine either did not change, or produced a small leftward shift in the discount function. A leftward shift occurred at 3.0 and 5.6 mg/kg for Rat P1, at 1.0 and 3.0 mg/kg for Rat P2, and at 5.6 mg/kg for Rat P3. At 3.0 mg/kg, Rat P2 chose the smaller reinforcer exclusively at all delay values. It should be noted that the discount function for Rat P3 at 3.0 mg/kg is the average of two determinations, one in which the curve was shifted dramatically to the right and one in which the curve was shifted slightly to the left. Unfortunately, this dose was not administered a third time.

Figure 6 shows dose-effect functions for morphine on the delay of indifference (top panels) and response speed (bottom panels), expressed as a percentage of saline data. For Rats P1 and P2, morphine produced dose-related decreases in delay of indifference. For Rat P3, 1.0 and 3.0 mg/kg increased, and 5.6 and 10.0 mg/kg slightly decreased, this measure (note the aforementioned variation in the effects of 3.0 mg/kg). For all rats, at least one (usually lower) morphine dose increased average response speed, although this effect sometimes was quite variable (e.g., Rat P2 at 1.0 mg/kg); higher doses decreased speed in all rats.

DISCUSSION

In the present study, reasonably consistent within-session, delay-discount functions were generated in individual rats. The general characteristics of these functions resembled those obtained from previous studies using a similar within-session procedure (e.g., Evenden & Ryan, 1996; 1999), as well as those obtained when delay parameters were manipulated across sessions (e.g., Green et al. 2004; Mazur, 1987, 1988; Richards et al., 1997). For 2 of the rats (P1 and P3), at least two doses of methylphenidate clearly increased choices of a larger, more delayed reinforcer, resulting in a shift of the delay-discount functions to the right. For the other 2 rats (P2 and P4), this effect was achieved following at least one dose under the altered delay sequence. In contrast,

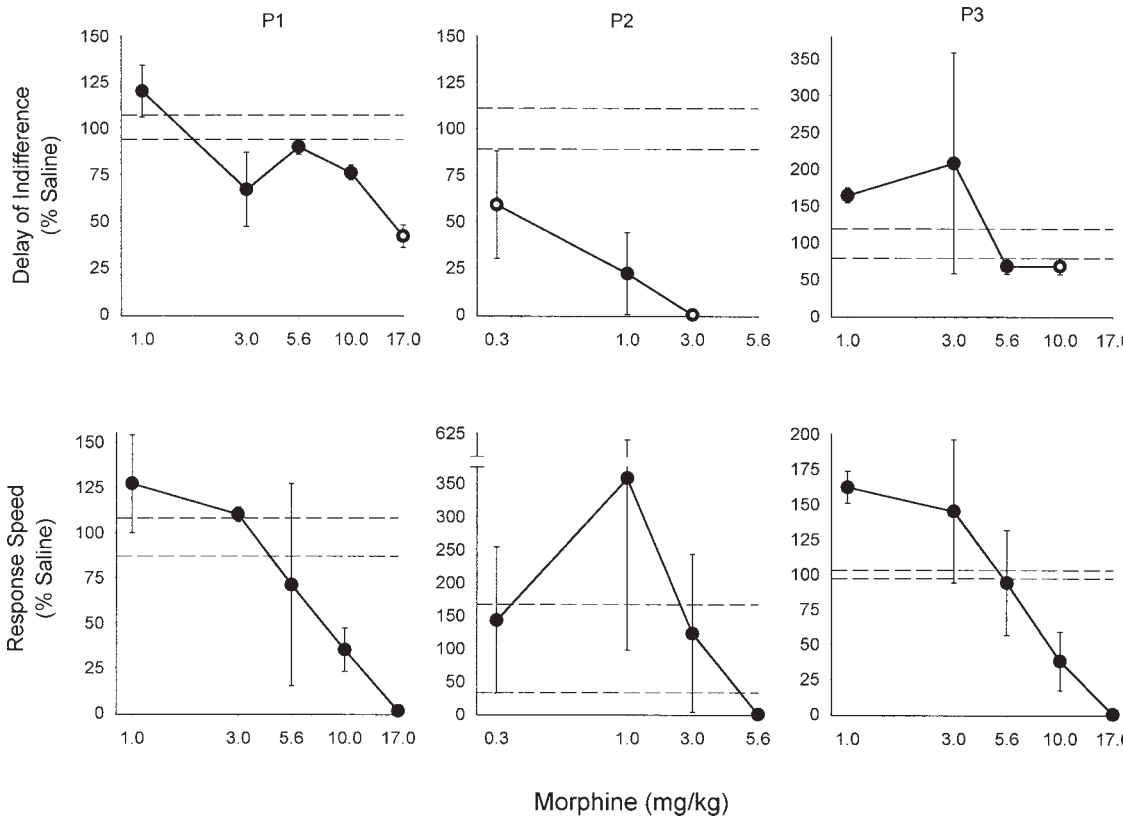

Fig. 6. Dose-effect functions for morphine on delay of indifference (top row) and response speed for Rat P1 (left column), Rat P2 (center column), and Rat P3 (right column), plotted as a percentage of data from saline sessions. Note that the *y* axes differ across rats. The absence of a data point in the top panels indicate that the dose was given but responding was suppressed to the extent that the delay of indifference could not be calculated (i.e., no blocks were completed). All other characteristics of this figure are as described in the captions of Figures 3 and 4.

morphine tended to shift the discount function to the left. The different effects of methylphenidate and morphine on choice are potentially important. Not only do they suggest a different profile of effects on self-control choices for these two drugs, they also indicate that the present procedure is sensitive to a range of drug effects. A shift to the right of the discount function, for example, is not an inevitable effect of pharmacological manipulation.

The methylphenidate-induced increases in self-control choice obtained in the present study with rats were similar to those obtained by Pietras et al. (2003) with humans, and similar to the effects of amphetamines obtained by several investigators (e.g., de Wit et al., 2002; Pitts & Febbo, 2004; Richards et al., 1999; Wade et al., 2000). Furthermore, although not overwhelming, the decreases in self-control choice produced by morphine here generally were comparable to the effects obtained by Kieres et al. (2004) under an adjusting-amount procedure. These similarities across studies likely are important. For example, the data from these studies illustrate some of the conditions under which psychomotor stimulants may provide therapeutic benefit and illustrate some of the conditions under which opiates may produce adverse effects on decision making. When combined with knowledge of the physiological and pharmacological actions of these drugs, these results suggest potential targets for investigation of the neurobiological mechanisms associated with behavioral processes involved in self-control choices.

There are important limitations, however, in drawing general conclusions about the drug effects on self-control choices. For example,

individual differences in the effects of stimulants are common in previous studies that report individual-subject data (e.g., Pietras et al., 2003; Pitts & Febbo, 2004). Indeed, there were clear differences in the effects of methylphenidate across rats in the present study. Similarly, Pietras et al. reported that methylphenidate failed to increase self-control choices in 4 of the 11 human subjects studied. Whether or not such variation across individuals is more characteristic with methylphenidate than with other stimulants is uncertain; reports of individual-subject data have been rare in previous studies with amphetamines (but see Pitts & Febbo, 2004).

The occasional reports of stimulant-induced decreases in self-control choices also must be considered (e.g., Charrier & Thiebot, 1996; Evenden & Ryan, 1996; Logue et al., 1992). It is not clear why these investigators found decreases, rather than increases, in self-control choices following stimulant administration. Richards et al. (1999) suggested that these results may relate to certain procedural characteristics. One possibility is that the differences in drug effects across studies depend on the nature of the stimulus conditions associated with the delays. In many of the studies that show stimulant-induced increases in self-control choices (e.g., Pietras et al., 2003; Pitts & Febbo, 2004; Richards et al., 1999; Wade et al., 2000; the present study), distinct stimulus conditions prevailed during the delays. After reinforcement, delay-correlated stimuli were turned off and the chamber was darkened until the start of the next trial. In the studies by Charrier and Thiebot and Evenden and Ryan, choice trials were initiated by extension of retractable levers (as in the present study). Following a choice of the larger, delayed reinforcer, the levers retracted (which also occurred after a choice of the immediate reinforcer), but apparently no other stimulus change occurred. Upon termination of the delay, food was presented, but again, no apparent stimulus change was programmed. That is, in those studies, the stimuli present during the delay and immediately after food presentation were the same. These differences in delay-correlated stimuli across studies may be important in determining drug effects. Cardinal et al. (2000) reported that effects of *d*-amphetamine on self-control choices differed depending upon whether or not the stimuli present during the delay to the larger reinforcer were unique (i.e., whether or not they also were present during the ITI).

Variability in the effects of stimulants on self-control choices, both within and across studies, has important implications. Although stimulants have been shown to attenuate patterns of behavior typically considered ''impulsive'' under a variety of procedures (e.g., de Wit et al., 2002), it could be argued that preference for a smaller, more immediate, reinforcer has become the gold standard test of ''impulsivity'' (see Logue, 1995). Given the variability in effects of stimulants under these procedures, broad conclusions that stimulant drugs have a uniform and fundamental effect on some construct termed ''impulsivity'' may be unwarranted.

Additional sources of control should be considered when interpreting drug effects under self-control procedures. Several of the studies, including the present one, have involved changing conditions within sessions (e.g., Evenden & Ryan, 1996, 1999; Pietras et al., 2003; Pitts & Febbo, 2004; Richards et al., 1999; Wade et al., 2000). Such procedures might recruit sources of control over choice other than reinforcement amount and delay. For example, in the present study it was necessary to conduct no-delay control sessions regularly (once or twice weekly) to maintain relatively consistent delay-discount functions. Despite regular exposure to the no-delay control, the tendency to choose the larger reinforcer decreased slightly across blocks during these sessions, particularly for Rats P2 and P4 (Figure 1). Evenden and Ryan (1996, 1999) and Cardinal et al. (2000) reported a similar effect. Furthermore, changing the sequence of delays for Rats P2 and P4 did not affect the discount functions as much as might have been predicted. Thus, under conditions in which reinforcement contingencies change within sessions, choice on a given trial can be controlled, at least in part, by variables other than (or perhaps only indirectly related to) the amount and delay values in effect on that trial. For example, an extensive history of exposure to escalating delays might establish a persistent pattern of behavior that is relatively resistant to short-term variation in conditions.

It also is possible that drug-induced ''perseveration'' may have played a role in the shifts of the discount functions obtained in the

present study. Under control conditions, all rats began each session by responding exclusively on the large-reinforcer option. As the delay increased, responding shifted to the small-reinforcer option. Methylphenidate may have increased, and morphine may have decreased, the tendency to continue engaging in the response that was prevalent at the beginning of the session (selecting the larger reinforcer). This interpretation of the present results is weakened somewhat, however, by reports that both stimulants and opiates tend to increase behavioral stereotypy, or perseveration (e.g., Hoelter, Tzschentke, & Schmidt, 1996; Loh, Smith, & Roberts, 1993). Nevertheless, the contribution of perseveration could be addressed by arranging a decreasing sequence of delays within the session (see Cardinal et al., 2000), or by presenting the delays in a random order with each in the presence of a distinctive stimulus.

Although methylphenidate and morphine affected choice differently in the present study, both drugs tended to decrease response speed at the higher doses; at lower doses, morphine occasionally increased response speed. With methylphenidate, the rightward shifts in the discount curves occasionally were accompanied by decreases in response speed, but this was not always the case. Average response speed was unchanged in several instances in which the average delay of indifference was increased (see Figures 3 and 4). With morphine, the relations between changes in response speed and changes in delay of indifference were inconsistent (see Figure 6). Thus it seems unlikely that the effects of these drugs on choice depended upon their effects on response speed. Interestingly, although individual-subject data were not presented, Kieres et al. (2004) reported morphine-induced decreases in self-control choices only at doses that produced statistically significant *decreases* in speed with which the rats initiated the trials and *increases* in the speed with which choices were made. They interpreted the former as a decrease in motivation and the latter as an increase in impulsivity. At this point, however, the specific relation, if any, between drug-induced changes in self-control choices and response speed has not been clarified sufficiently.

Response speed under baseline conditions in the present study, however, may have played an indirect role in determining the effects of methylphenidate on choice, particularly with Rat P2. For this rat, methylphenidate did not appreciably alter the discount function at the original delays. However, Rat P2 was particularly slow to respond under nondrug conditions at the original delays, and response speed was quite sensitive to the effects of methylphenidate. This may have prevented any effect of methylphenidate on choice from being expressed at the moderate doses. Under the altered delays, Rat P2's response speed increased under nondrug conditions such that all the trials typically were completed within the time limit. At these delays, 5.6 mg/kg methylphenidate shifted the discount function to the right.

Despite the inconsistencies in drug effects, particularly those of stimulants, under self-control procedures both within and across studies, and the associated methodological and theoretical issues, it is worth considering some of the potential behavioral mechanisms that might be involved in the effects of methylphenidate and morphine on choice in the present study. The most obvious interpretation involves a drug-induced change in the sensitivity to the discounting effects of reinforcement delay. That is, it is possible that methylphenidate decreases and morphine increases sensitivity to the discounting effects of reinforcement delay. Such an interpretation for methylphenidate is consistent with data reported by Pitts and Febbo (2004). They used an equation based upon the generalized matching law (e.g., Baum, 1974) and hyperbolic discounting (Mazur, 1987) to obtain parameter estimates for sensitivity to reinforcement delay in pigeons responding under a self-control procedure. They found that methamphetamine-induced increases in choices for a larger delayed reinforcer were consistently accompanied by decreases in the estimates for sensitivity to reinforcement delay. At present, it is unclear whether or not the effects of morphine in the present study indicate an increased sensitivity to reinforcement delay.

A drug-induced change in self-control choice also could reflect a change in the sensitivity to the effects of reinforcement amount. Thus it is possible that methylphenidate increased self-control choices in the present study by increasing sensitivity to reinforcement amount. Conversely, morphine

may have decreased self-control choices by decreasing sensitivity to reinforcement amount; the decreased choice of the larger reinforcer at the 0-s delay for Rat P2 is consistent with this interpretation. An account of the present data in terms of sensitivity to reinforcement amount is consistent with previous data showing that methylphenidate can increase (Heyman, 1992) and that opiates can decrease (Egli, Schaal, Thompson, & Cleary, 1992; Lancaster & Dallery, 1999) sensitivity to reinforcement rate. Although this interpretation is possible, its application to the effects of methylphenidate in the present study is weakened by data reported by Pitts and Febbo (2004). They found that, although effects on estimates of sensitivity to reinforcement amount were somewhat inconsistent across pigeons, methamphetamine tended to decrease, rather than increase, this measure. Note, however, that only two reinforcement amounts were used in both the Pitts and Febbo study and the present study. A more definitive assessment of the effects of drugs on sensitivity to reinforcement amount requires study of a wider range of amounts.

Several investigators have suggested that stimulant-induced increases in self-control choices may reflect effects on conditioned reinforcement (e.g., Pietras et al, 2003; Richards et al., 1999). Results from several experiments indicate that stimulants, including methylphenidate, can increase the effectiveness of conditioned reinforcers (e.g., Files, Branch, & Clody, 1989; Hill, 1970; Robbins, 1978). Thus, in the present study, methylphenidate may have increased self-control choices by increasing the conditioned-reinforcing effectiveness of the stimuli associated with the delay to the larger reinforcer. Pitts and Febbo (2004), however, found that methamphetamine increased self-control choices under conditions in which both the larger and smaller reinforcers were presented after signaled delays (the delay to the larger reinforcer usually was longer). Because a choice of either the larger or the smaller reinforcer resulted in presentation of a conditioned reinforcer, their results are difficult to interpret on the basis of a drug-induced enhancement of conditioned reinforcement. Thus clarification of the role of drug-induced changes in conditioned reinforcement as a basis for stimulant effects on self-control choice awaits additional research.

Finally, the possibility that the present results relate to drug-induced changes in ''timing'' should be considered. Following certain doses of psychomotor stimulants, subjects respond earlier than usual under procedures often used to assess temporal discrimination (e.g., Eckerman, Segbefia, Manning, & Breese, 1987; Maricq, Roberts, & Church, 1981; Meck, 1983). That is, in these procedures, stimulants appear to produce an overestimation of the passage of time; subjects respond as if more time has elapsed than is actually the case. Interestingly, a straightforward application of this interpretation predicts effects of methylphenidate opposite of those obtained here. That is, if a dose changed the effect of a 10-s delay to that of a longer (e.g., 20-s) delay, then we would expect the delay-discount function to shift to the left. Thus the present data with methylphenidate are difficult to interpret as an overestimation of delay. Some of the data with morphine (a leftward shift of the discount function), however, are consistent with this interpretation. It should be noted, however, that results from a variety of studies with both stimulants and opiates under procedures involving temporal discrimination are readily interpreted as rate-dependent effects (e.g., Knealing & Schaal, 2002; Odum, Lieving, & Schaal, 2002), in which drug administration increases low-probability behavior and/or decreases high-probability behavior (see Dews, 1958; Dews & Wenger, 1977). Neither the results for methylphenidate nor morphine on choice in the present study, however, appear to reflect ''purely'' rate-dependent drug effects. Such effects likely would have occurred as a flattening of the discount function, in which the high probability choices of the larger reinforcer at the short delays were decreased and the low probability choices of the larger reinforcer at the longer delays were increased.

In summary, at intermediate doses, methylphenidate tended to increase and morphine tended to decrease choices of a signaled larger, delayed reinforcer in rats. The specific behavioral mechanism(s) involved in these effects is (are) not yet clear, but a drug-induced change in the sensitivity to reinforcement delay is a viable possibility. Variability in the effects of drugs on self-control choices, both within and across studies, however, suggests that caution may be in order. The

various procedures used to study self-control choices likely contain unique, and potentially important, sources of control over drug effects that may not be characterized easily within the framework of the commonly used construct of ''impulsivity.''

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