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THE EFFECTS OF SMOKED MARIJUANA ON PROGRESSIVE-INTERVAL SCHEDULE PERFORMANCE IN HUMANS

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In three experiments, 8 human subjects participated in a study of the effects of smoked marijuana on progressive-interval schedule performance. A two-component chained progressive-interval fixed-interval schedule of point delivery was used. In the progressive-interval component, the interval length began at 20 s and increased either geometrically or arithmetically (by either 20 s, 40 s, 80 s, 100 s, or 160 s) on each subsequent interval. After this interval elapsed, a single button press produced the fixed-interval component, with a total of five reinforcers of varying magnitude ($0.05, $0.20, or $0.40) available on a fixed-interval 20-s schedule. After the five reinforcer deliveries, the schedule returned to the initial progressive-interval component. Several relationships were found among rates of responding, postreinforcement pauses, and drug administration in the progressive-interval component: (a) Postreinforcement pauses increased as the temporal requirements of the progressive-interval schedule increased; (b) rates of responding during successive progressive-interval components rapidly decreased to low rates of responding after the first few progressions; (c) postreinforcement pauses decreased systematically as dose of smoked marijuana increased; and (d) rates of responding increased after smoking active marijuana but not after smoking placebo cigarettes. Results are discussed in the context of behavioral control and relevance to other studies that have investigated the effects of smoked marijuana on schedule performance.

Key words: behavioral pharmacology, progressive-interval schedule, marijuana, schedule control, magnitude of reinforcement, postreinforcement pause, rate of responding, button press, humans

Under progressive-interval (PI) schedules, reinforcement becomes available after an interval of time has passed since the previous reinforcement. But rather than the interval's duration remaining constant, as in fixed-interval (FI) schedules, successive intervals increase in duration, often according to a geometric or arithmetic progression. An arithmetic progression increases by adding a constant interval value to each successive interval (e.g., from 3 s, to 6 s, to 9 s, and so forth); a geometric progression increases by adding a constant percentage to each successive interval value (e.g., from 3 s, to 6 s, to 12 s, and so forth). All responses other than the first response after the interval has elapsed have no programmed consequence. Normally, PI schedule performance is evaluated using one or more of the following response measures: postreinforcement pauses (PRPs), interresponse time distributions (IRTs), and/or rates of responding. If responding is controlled by a PI schedule, PRPs and IRTs increase, and rates of responding decrease as the schedule's interval durations increase.

Only a few studies have been conducted with PI schedules (Findley, 1958; Hackenberg & Axtell, 1993; Harzem, 1969; Innis & Staddon, 1971). Some have focused on PI schedules as a methodological tool to study pigeons' preference and switching behavior (Findley, 1958). Others have focused on more fine-grained details of PI schedule performance of rats (Harzem, 1969) and pigeons (Innis & Staddon, 1971).

Progressive-interval schedule performance was first studied because it was thought to offer some unique perspectives into the study of temporal discrimination that were not offered by cyclic schedules of reinforcement (see Harzem, 1969). Although cyclic schedules (Staddon, 1964, 1967) usually include abrupt alternations of only two or three temporal interval values, PI schedules change gradually according to a systematic algorithm, and all intervals differ within a session. With PI schedules, complex temporal discriminations can be studied. Harzem, in his experiments, used several arithmetic schedules (PI 15 s, PI 30 s, PI 45 s, PI 60 s, and PI 90 s) and geometric schedules (PI 60 s increased by 20%; PI 10 s increased

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by 20%). On these schedules, despite the absence of any programmed changes in stimuli, bar pressing by rats adjusted to the changing temporal requirements of the PI schedules. Postreinforcement pauses were systematically controlled by the schedule, with little responding occurring until each interval's temporal requirement had nearly elapsed, although little time elapsed between the availability of the reinforcer and occurrence of the reinforced response. These response adjustments occurred even when temporal durations were all different within a session and became very long. The degree of response efficiency, or schedule control, that was ultimately established appeared to be dependent on whether the intervals progressed arithmetically or geometrically. In the former case, the proportion of change between successive intervals became increasingly smaller as the schedule progressed and hence was difficult to discriminate; at some point those intervals approximated an FI schedule. In the latter case, the proportion of change between successive intervals was held constant and hence was easy to discriminate.

Similar results have been observed using more complex PI schedules. In one set of studies, pigeons' temporal tracking was investigated using PI schedules that cycled, such that the temporal requirements first increased and then decreased (Innis & Staddon, 1970, 1971). Within each session there were four cycles, each with its own incremental value ranging from 2 s to 40 s. In other words, within a session four consecutive PI schedules were used, and in each case (or cycle) the schedule both increased and decreased. As in previous experiments (Harzem, 1969), PRPs closely approximated the temporal requirements of the PI schedules. In addition, these researchers found that (a) added discriminative stimuli corresponding with the schedule's increasing or decreasing cycle improved temporal tracking compared to schedules without added stimuli, and (b) temporal tracking of the schedule's requirements was more stable under logarithmic than under geometric progressions.

The present study was conducted to examine PI schedule performance in humans and to characterize the behavioral effects of smoked marijuana. The PI schedule's complex temporal contingencies were of particular interest because marijuana has been suggested to produce overestimations of elapsed time (Hicks, Gualtieri, Mayo, & Perez-Reyes, 1984; Tinklenberg, Kopell, Melges, & Hollister, 1972). For this reason, we hypothesized that marijuana would significantly affect subjects' performance (i.e., decrease PRP durations). In Experiment 1, behavioral data were collected to determine how humans would respond under PI schedules; several PI schedules (including geometric and arithmetic progressions) were used as well as some reinforcer-magnitude manipulations. In Experiment 2, an arithmetic PI 20-s schedule was studied at three active doses of marijuana and a placebo. And in Experiment 3, the effect of smoking the highest potency marijuana cigarette was studied under three arithmetic PI schedules (PI 20 s, PI 60 s, and PI 80 s).

EXPERIMENT 1

Experiment 1 was conducted to collect some initial parametric data. More specifically, we examined whether responding by humans under a PI schedule was sensitive to (a) variations in the PI incremental value of the PI component, (b) variations in reinforcement magnitude, and (c) the influence of arithmetic versus geometric progressions.

METHOD

Subjects

Two experimentally naive males (S-683 and S-723) participated in this experiment: S-683 was 30 years old, reported 12 years of education, and weighed 75 kg; S-723 was 21 years old, reported 13 years of education, and weighed 65 kg. Neither reported illicit drug use.

Apparatus

During experimental sessions, subjects sat in a sound-attenuating chamber (1.32 m by 1.62 m by 2.23 m) that contained a response panel and a computer monitor. The response panel was a metal box (43.2 cm by 26.0 cm by 10.2 cm) containing three push buttons, each labeled with a letter (A, B, or C). The panel's wire lead was of sufficient length to allow the subject to move it onto his lap or to place it on a shelf (28.0 cm wide) that extended across the full length of the front wall (83.5 cm above the chamber's floor) in front of the subject's chair. Located just behind this shelf,

at the subject's eye level, was an Apple® monochrome monitor. Also located in the chamber was a ventilation fan, the noise from which masked extraneous sounds, and a ceiling light.

Experimental events were controlled and responses monitored by an Apple® IIGS computer equipped with an Applied Engineering I/O 32 interfacing system. In addition, a Gerbrands cumulative recorder (Model C-3) provided a continuous record of responding and experimental events.

Procedure

Subjects were recruited through advertisements in local newspapers as "paid volunteers for behavioral research"; no information was given as to the content of the research. Following a preliminary telephone interview and screening, potential subjects were invited to come into the laboratory for an in-depth interview.

Initially, subjects were screened for possible psychiatric or medical illness; once in the study, they were screened daily for alcohol and other drug use. The initial screening included the administration of a survey that included both medical and psychiatric questions. Detection of any current or past psychiatric disorder (including alcoholism and substance dependence) or any physical illness was grounds for exclusion. Breath alcohol levels (using an Intoximeter Model 3000 III) and urine samples were collected from each subject every morning to monitor compliance with the experimental protocol. Urine samples were tested using the Enzyme Multiple Immunoassay Technique—Drug Abuse Urine assay (EMIT d.a.u.® by SYVA Corporation). This procedure allowed us to screen for cannabinoids, cocaine, barbiturates, benzodiazepines, phencyclidine, and opiates as well as approximately 150 other metabolites of therapeutic agents and drugs of abuse (results from these tests were available approximately 1 hr prior to the subject's release). If alcohol was detected, the subject was sent home. If drugs (including alcohol) were detected on more than one occasion, the subject's participation was terminated.

Instructions. Instructions prior to the first session were minimal and were limited to general statements concerning the apparatus and the scheduling of the sessions. Subjects were never told to press buttons to obtain reinforcement. Rather, statements were descriptive and included phrases like "Here are three response buttons and a computer monitor. On the monitor, letters will periodically appear and your earnings will be displayed"; no instructions about the contingencies were provided. Subjects were also told that they would participate in five sessions, each 60 min in duration, scheduled periodically throughout the day with the first session starting at 8:30 a.m. and the last one ending at 4:00 p.m.

Progressive-interval schedule. The schedule used in the experimental sessions was a chained schedule with two components: a PI component (that increased either arithmetically or geometrically) and an FI (point-delivery) component. In the PI component, the interval began at 20 s and was lengthened by t s at each successive exposure to this component—the arithmetic progression. In other words, each successive interval in this component was equal to the sum of the previous interval's requirement plus t s. The constant, t s, was either 20 s, 40 s, 80 s, or 160 s. For the geometric schedules, the first interval was always 20 s long, and successive intervals were double the previous interval's value. The PI component was paired with the letter A (2.0 cm by 2.0 cm), and the subject's earnings were displayed on the monitor. Responses on Button A before an interval had timed out were counted but had no programmed effects. The first response made on button A after an interval had timed out completed the first component (deleting the letter A) and advanced the schedule to its second component (producing the letter B). In the second component, five reinforcers (earnings added to the subject's counter) were available under an FI 20-s schedule. After a 20-s interval had timed out, the subject's first B button response produced a reinforcer, the earnings (either \$0.05, \$0.10, or \$0.40) were added to his counter, and the next FI was initiated. After the subject received five successive reinforcers, the schedule returned to the PI component. These components alternated for 60 min, at which time the session terminated.

All subjects participated in five (60-min) sessions each day using a constant PI schedule value until they met a stability criterion. Subjects spent a minimum of 20 sessions in each condition. Responding was considered stable if rates of responding during the final three sessions of a schedule condition did not show an upward or downward trend and each of

Table 1

PI schedules and drug manipulations for each subject in each experiment.

Experiment	Subject	Progression	PI schedule (s)	Reinforcer magnitude ($)	Drug doses (% w/w Δ-9 THC)
1	S-683 and S-723	arithmetic	20	0.10	
			40		
			80		None
			160		
		geometric	20	0.05	
				0.10	None
				0.40	
2	S-877, S-880, and S-915	arithmetic	20	0.10	½(1.77)
					1.77
					3.58
3	S-453, S-784, and S-794	arithmetic	20	0.10	3.58
			60		3.58
			100		3.58

the individual-session response rates did not differ by more than 10% of the mean rate. Once stability criteria were met, subjects were advanced to another PI schedule value. A summary of the schedule and reinforcer manipulations appears in Table 1. The sequence of schedule exposure was the same for all subjects: PI 20-s, PI 40-s, PI 80-s, and PI 160-s arithmetic schedules with $0.10 as reinforcement, followed by the PI 20-s geometric schedule under $0.05, $0.10, and $0.40 reinforcer magnitudes.

Results

Cumulative records illustrating the performances generated by the arithmetic and geometric PIs are shown in Figure 1 (taken from a subject's 10th session in each condition). Responses were distributed in a manner in which few, if any, responses were emitted immediately following a reinforcer delivery, and most responses occurred near the end of the interval.

Postreinforcement Pauses

Assessments of postreinforcement pauses, time elapsed from the delivery of the last reinforcer of each cycle to the first response in each interval, were based on the final session in each condition. Responding generally came under control of the changing temporal requirements of the arithmetic and geometric PI schedules and was affected little by changes in reinforcer magnitude. The PRP analysis for

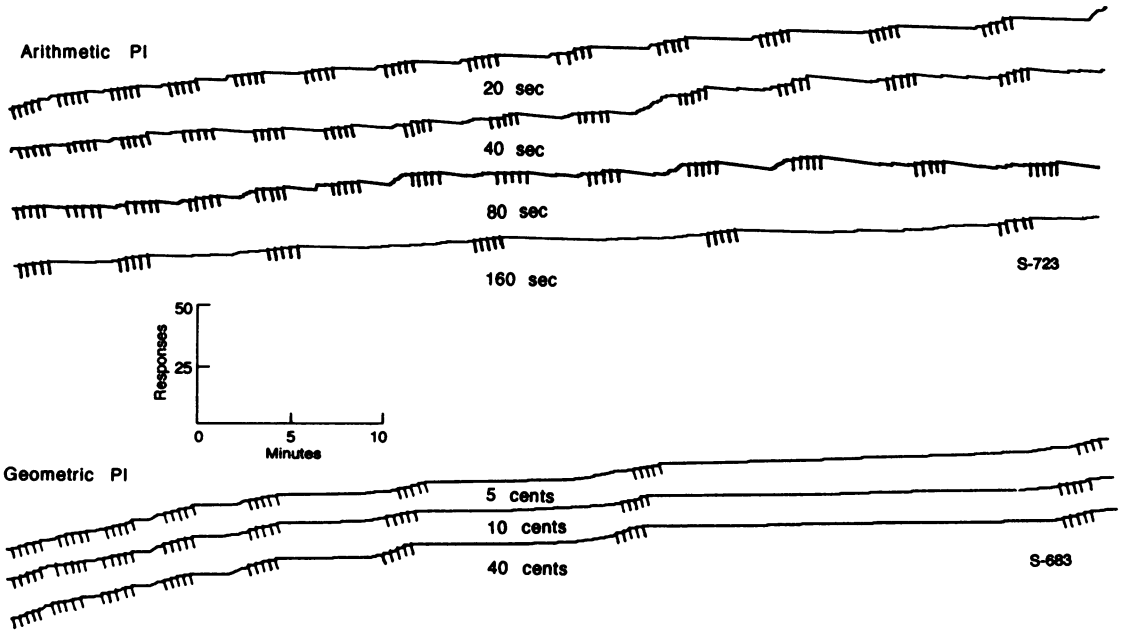

Fig. 1. Samples from 2 subjects' cumulative records. Cumulative records are shown for S-723 (top) on the four arithmetic schedules (PI 20 s, PI 40 s, PI 80 s, and PI 160 s). Cumulative records are shown for S-683 (bottom) on the geometric PI schedule at three reinforcer magnitudes ($0.05, $0.10, and $0.40). Each series of vertical pip marks indicates reinforcer deliveries and separates successive PI components.

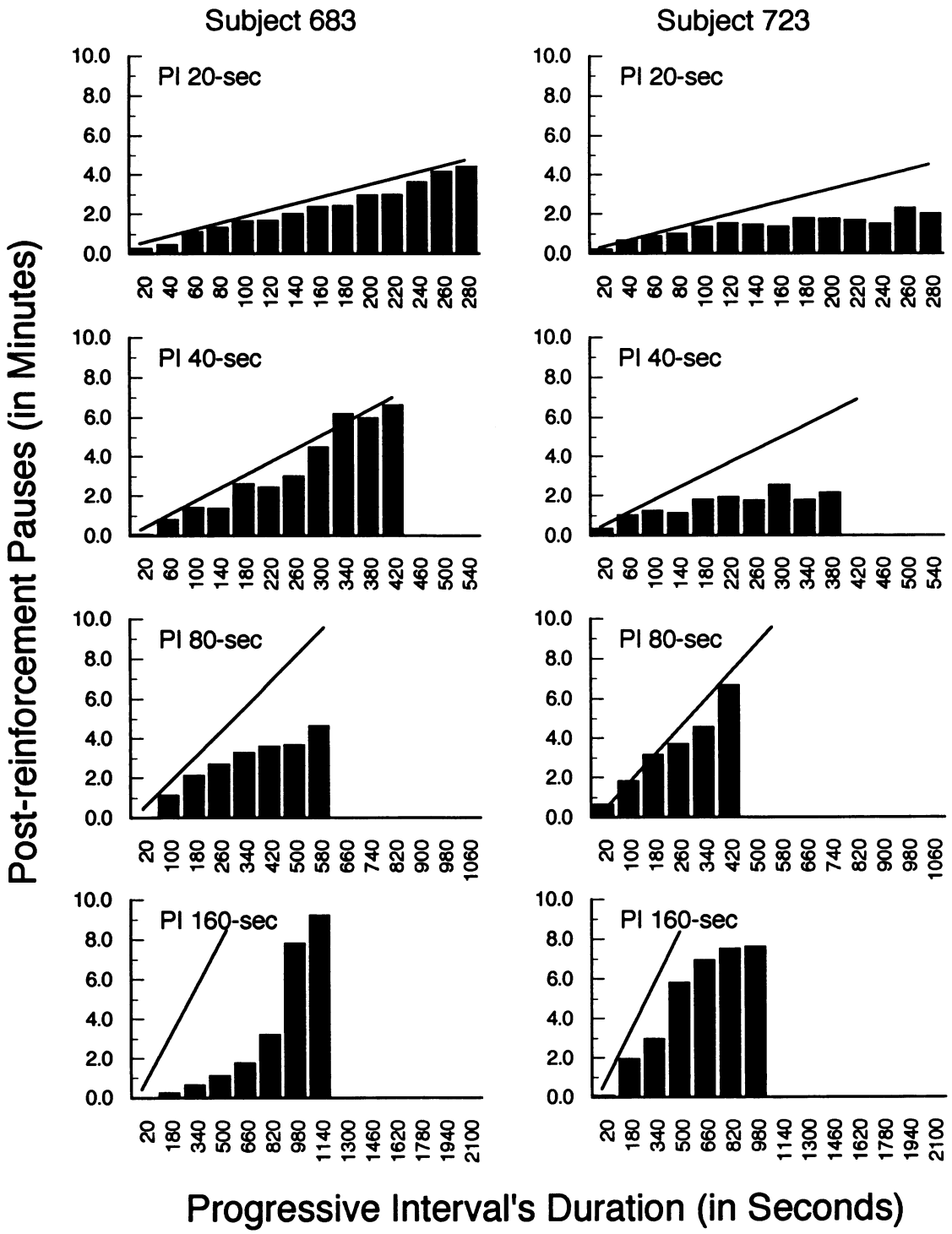

Fig. 2. Postreinforcement pauses for S-683 and S-723 are shown for the PI 20-s, PI 40-s, PI 80-s, and PI 160-s arithmetic schedules. All PI schedules began with a 20-s requirement and then incremented by their respective schedule values on successive times through the PI schedule. Each bar represents the PRP (in minutes) for each particular interval completed in a 60-min session. The number of bars in each graph corresponds with the number of PI components completed in the session. The black lines represent postreinforcement pauses of the same duration as the PI duration on the abscissae.

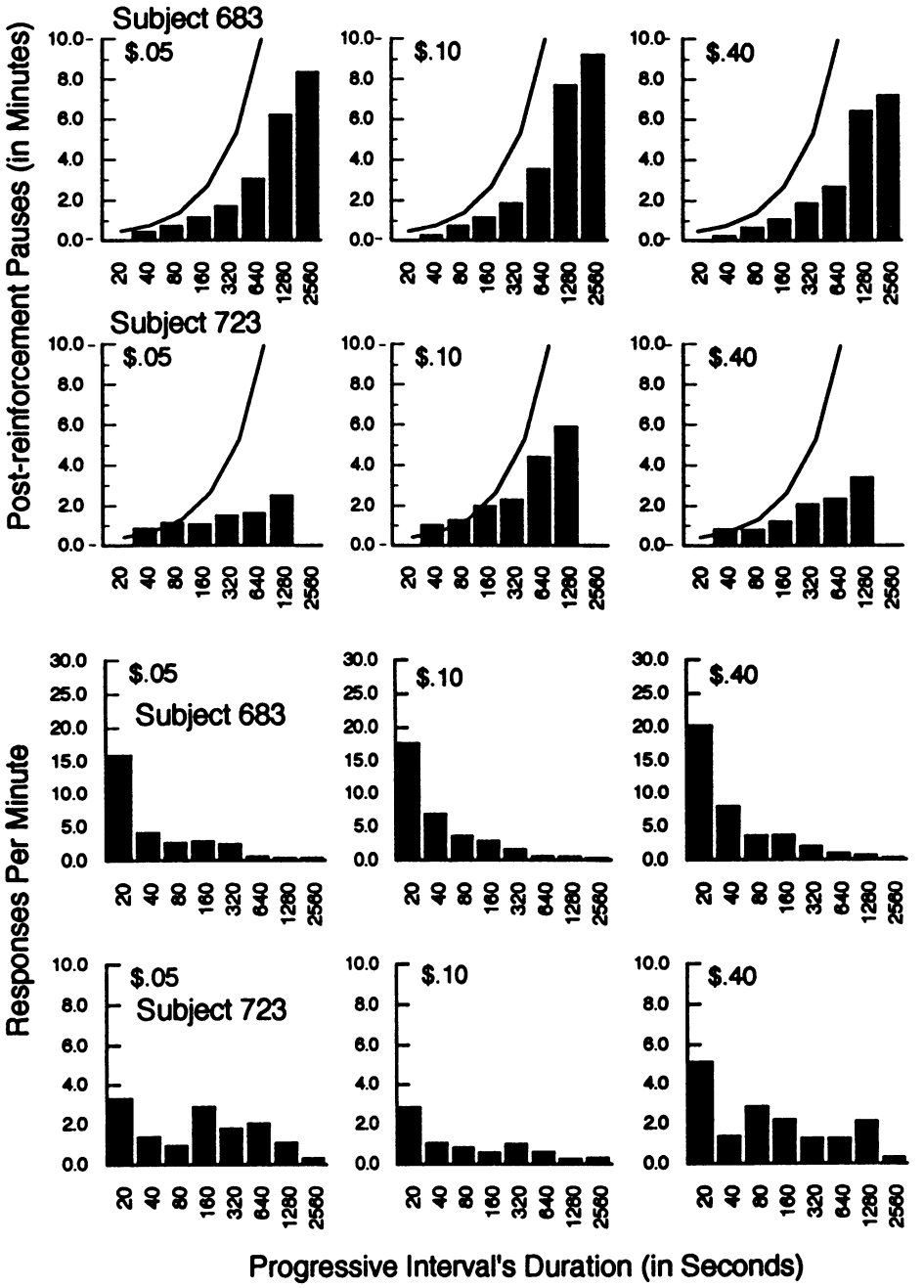

Fig. 3. The PRPs for S-683 and S-723 (top) for the geometric PI schedule at three reinforcer magnitudes ($0.05, $0.10, and $0.40). The PI schedule's temporal requirement began at 20 s and increased geometrically (doubling) during each successive time through the schedule. Each bar represents the PRP (in minutes) for each PI component completed in a 60-min session. The accelerated black lines represent postreinforcement pauses of the same duration as the PI duration on the abscissae. The bottom panel shows the rates of responding (in responses per minute) for these same subjects and sessions.

the arithmetic PI schedules is shown in Figure 2, and the analysis for the geometric PI schedules is shown in Figure 3 (top panels). Under both the arithmetic (including PI 20-s, PI 40-s, PI 80-s, and PI 160-s schedules) and geometric PI conditions ($0.05, $0.10, and $0.40 point values), PRPs increased as a function of increases in the interval value of the schedules (actual PI durations are depicted in each of the graphs as a black line). Changing the magnitude of the reinforcer (in the geometric conditions; Figure 3) had no systematic effect on PRPs.

Rates of Responding

Rates of responding were calculated from each successive PI interval within a session. For these calculations, we used the last session meeting the stability criterion (the same session used for the above PRP analysis). There was an inverse relationship between the PRPs described above and rates of responding under the arithmetic (Figure 4) and geometric (Figure 3, bottom panels) PI schedules. That is, PRPs increased and rates of responding decreased on successive intervals. Moreover, the arithmetic PI schedules (Figure 4) with longer temporal incremental requirements (e.g., PI 160 s) controlled lower response rates than the schedules with shorter incremental temporal requirements (e.g., PI 20 s). There were no obvious effects of the schedule's incremental value or progression type on rates of responding in the FI component of the schedule. Rates of responding for the last day in each condition appear in Table 2.

Table 2

Rates of responding in the fixed-interval component of the schedule for the 2 subjects in Experiment 1.

Subject	PI schedule (s)	Responses per minute, Session 1	2	3	4	5
S-683	PI 20	5.2	5.4	3.9	3.8	3.1
	PI 40	2.8	2.3	2.9	5.5	3.1
	PI 80	4.5	4.1	3.0	4.5	3.5
	PI 160	4.7	3.3	2.8	3.1	2.7
	geometric ($0.05)	5.1	3.6	4.1	4.2	3.5
	geometric ($0.10)	4.1	3.4	3.4	3.1	3.3
	geometric ($0.40)	5.1	3.4	2.9	4.5	4.0
S-723	PI 20	3.2	3.5	3.0	3.9	3.7
	PI 40	3.1	3.1	3.8	5.3	3.4
	PI 80	2.9	2.7	2.7	5.5	2.9
	PI 160	4.2	5.1	6.1	4.0	2.8
	geometric ($0.05)	1.6	1.7	2.0	1.9	1.7
	geometric ($0.10)	1.3	1.4	1.3	1.6	1.4
	geometric ($0.40)	2.2	2.1	1.5	2.3	1.9

EXPERIMENT 2

In Experiment 1, PRPs approximated the schedule's temporal requirements and were accompanied by corresponding decreases in rates of responding as the PI schedule progressed within a session. In Experiment 2, we were interested in how PRPs and rates of responding on PI schedules were affected by three different doses of smoked marijuana.

METHOD

Subjects and Apparatus

Three additional experimentally naive male subjects were recruited. These subjects' mean age was 30 years old (range, 21 to 36 years old), their mean number of years of education was 13 (range, 12 to 16 years), and their mean body weight was 75 kg (range, 54 to 88 kg). Two subjects were Hispanic and 1 was African American. Mean reported frequency of marijuana use was approximately one occasion per month (range, 0.5 to 2.0 occasions). For inclusion in this study, subjects had to report using marijuana at least once during the preceding 6 months but no more often than five occasions per month. These drug-use criteria were established to ensure use of experienced subjects while avoiding behavioral or physiological tolerance (e.g., Babor, Mendelson, Gallant, & Keuhnle, 1978; Mendelson, Keuhnle, Greenberg, & Mello, 1976). These subjects reported previous experience with a number of other drugs, including opiates, narcotics, LSD, and benzodiazepines.

The apparatus was the same as in Experiment 1.

Procedure

Because these subjects were recruited for a drug-administration study, the recruitment and screening procedures were somewhat different from those used in Experiment 1. The initial screening included (a) an examination by a board-certified psychiatrist that included a standard psychiatric interview and the Schedule for Affective Disorders and Schizophre-

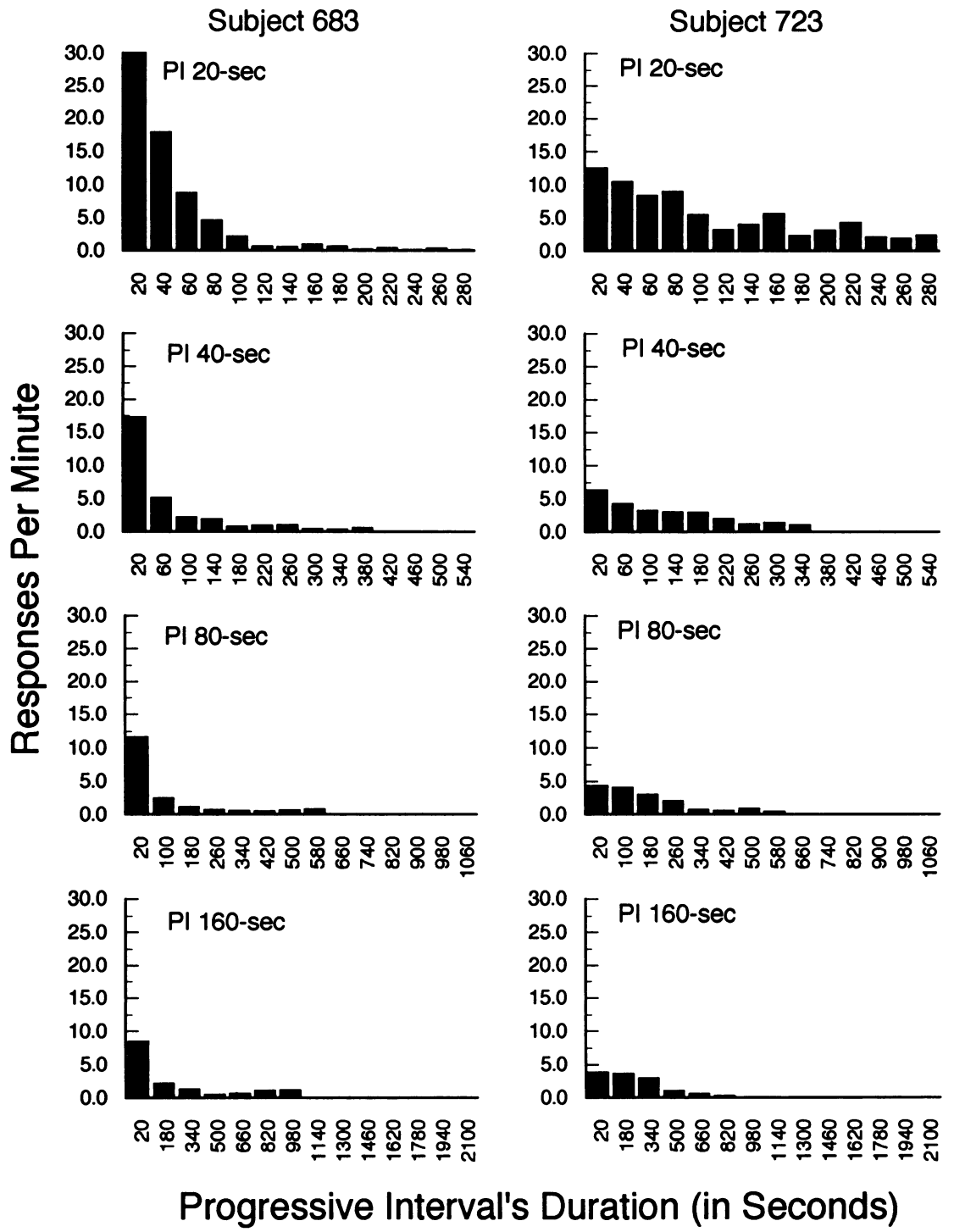

Fig. 4. Rates of responding for S-683 and S-723 in the PI 20-s, PI 40-s, PI 80-s, and PI 160-s arithmetic schedules. All PI schedules began with a 20-s requirement and then incremented by their respective schedule values on successive times through the PI schedule. The exact temporal requirements (in seconds) of each successive interval are shown along the horizontal axis. Each bar represents the responses per minute made during each interval completed in a 60-min session. The number of bars corresponds with the number of PI components completed in the session.

nia—Lifetime (Spitzer & Endicott, 1978) and (b) a physical examination by a nurse practitioner. Grounds for exclusion included the detection of any current or past psychiatric disorder (including alcoholism and substance dependence) or any physical illness. Subjects were also excluded if they had previously participated in a drug-treatment program. Once in the experiment, breath alcohol (using an Intoximeter Model 3000 III) and urine samples were screened daily to ensure drug abstinence outside the experiment. Urine was tested by EMIT d.a.u. assay for the presence of all major classes of drugs of abuse plus many therapeutic drugs. The semiquantitative analysis of cannabinoid levels (ng/mL) allowed the monitoring of Δ-9-tetrahydracannabinol (Δ-9-THC) levels in each subject's urine, and this helped to monitor marijuana use outside the study (for more detail see Cherek et al., 1993). If alcohol was detected, the subject was sent home. If illicit drugs or alcohol was detected on more than three occasions, the subject's participation was terminated.

Administration of marijuana. After the initial few days of PI schedule exposure, the placebo (and later active) marijuana-cigarette administration was initiated. Marijuana cigarettes (weighing 900 mg) contained 0.0001%, 1.77%, and 3.58% w/w Δ-9-THC, respectively, and were supplied by the National Institute on Drug Abuse, Research Technology Branch. Marijuana smoking occurred daily in a ventilated Plexiglas room immediately preceding each subject's second session of the day. Marijuana administration followed a paced procedure that has been reported previously (Renault, Schuster, Heinrich, & Freedman, 1971). In brief, colored lights signaled when the subject was to inhale, hold his breath, and exhale smoke from the marijuana cigarette: This procedure involved a 2-s inhalation, a 10-s breath hold, and then an exhalation. Subjects repeated this sequence 10 times at the rate of one puff every 30 s. An experimenter monitored the subject's smoking and took readings of blood pressure and heart rate before and after smoking. Also, immediately after smoking marijuana, the subject completed a symptom questionnaire. Each subject was asked to rate (on a 5-point scale) the effect of the marijuana cigarette and whether he was experiencing heart pounding, light-headedness, or a typical marijuana "high."

Every day the subject smoked two halves of a marijuana cigarette and the dose of each half was varied; the cutting of the cigarettes was necessary to obtain three different doses of marijuana. On placebo administration days, the subject smoked two placebo halves. On drug administration days, the subject smoked two halves that, in combination, produced three drug doses (listed in ascending order): (a) low = 1.77% and 0.0001% w/w Δ-9-THC (placebo); (b) medium = 1.77% and 1.77% w/w Δ-9-THC; and (c) high = 3.58% and 3.58% w/w Δ-9-THC. These three combinations were selected because they roughly approximated a logarithmic increase in dose.

In this experiment the PI schedule value was kept constant at 20 s, and only drug dose was manipulated. Each subject was exposed to the arithmetic PI 20-s schedule and was stabilized for a minimum of 20 sessions before being given an active dose of marijuana. After a subject's behavior became stable and his urine was free of cannabinoids (and other drugs), an active dose was given. Subjects received the three doses in an ascending dose order. A minimum of 72 hr separated the smoking of active cigarettes. The experiment was complete after all 3 subjects had experienced all three doses of marijuana.

Results

Each subject's results are summarized in terms of two dependent measures: PRPs and rates of responding. Each of these measures was calculated using the second session of the day (the session immediately following the smoking administration).

The PRP analysis for the 3 subjects (S-877, S-880, and S-915) on the arithmetic PI 20-s schedule under marijuana and placebo conditions is shown in Figure 5 (left panel). Each drug-dose point represents the cumulative total of PRPs within a single session; each placebo point represents the mean cumulative total of PRPs for placebo days (calculated using the second session from each day prior to an active dose day). There was an inverse relationship between dose of smoked marijuana and PRPs: As dose increased, PRPs decreased. More specifically, the low dose (1/2 [1.77%] w/w Δ-9-THC) had little effect; the medium dose (1.77% w/w Δ-9-THC) produced a slight decrease; and the highest dose (3.58% w/w

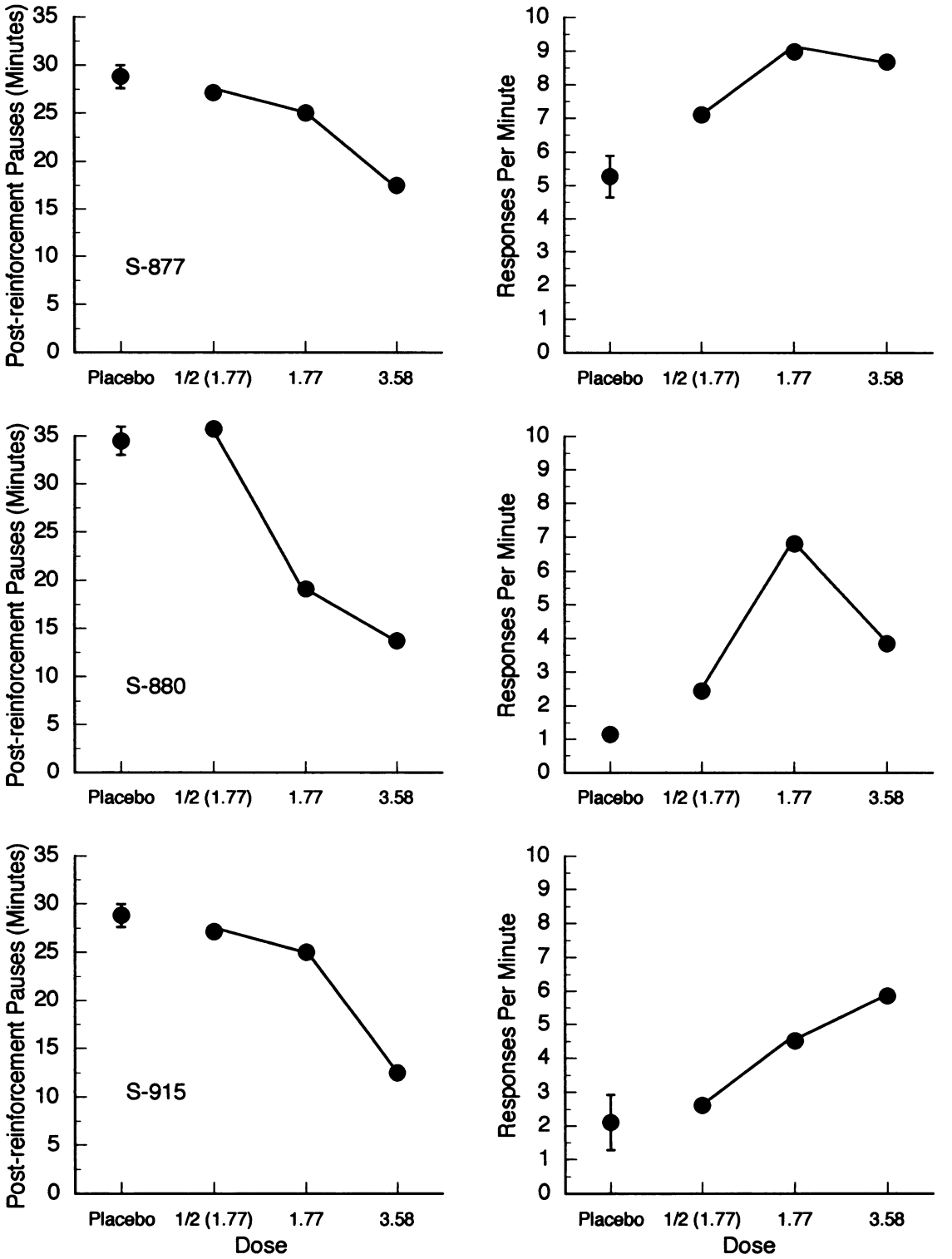

Fig. 5. Each subject's PRPs (left column) and responses per minute (right column) on the PI 20-s schedule after smoking either an active marijuana dose or a placebo. The three individual doses of smoked marijuana are indicated along the *x* axis. In the PRP graphs, each point represents the total PRPs (in minutes) during the session immediately following drug administration; in the response-rate graphs, each point represents the responses per minute (in the PI component) for these sessions. Error bars on the placebo points represent one standard error of the mean calculated from three placebo control sessions (see text).

Δ-9-THC) produced a very discernible decrease in PRPs.

The response-rate analysis for the 3 subjects on the arithmetic PI 20-s schedule under marijuana and placebo conditions is shown in Figure 5 (right panel). Each point represents responses (per minute) made during the PI components of the schedule within a session. These measures were calculated using the second session of the day (session following smoking marijuana). The placebo data were taken from the day immediately preceding an active-dose administration day (second session). Compared to placebo, rates of responding increased in all subjects after smoking active doses of marijuana (1/2 [1.77%], 1.77%, and 3.58% w/w Δ-9-THC, respectively). For S-915, rates of responding increased as dose increased. For S-877 and S-880, however, rates of responding decreased at the highest dose relative to the moderate dose.

Rates of responding in the FI component of the schedule varied across subjects following both placebo and active-dose cigarettes, and no systematic effects were observed.

Subjective Measures and Heart Rates

Ratings of the four items on the smoking questionnaire and subjects' heart-rate measures appear in Table 3. Ratings of marijuana effects increased as a function of dose. Heart rate increased more after smoking active marijuana than after placebo, and increases were dose related.

EXPERIMENT 3

In Experiment 2, we investigated human PI schedule responding after the administration of three different marijuana doses and found that the most significant changes in PRPs occurred after smoking the highest dose (3.58% w/w Δ-9-THC). In Experiment 3, we were interested in studying whether the effect of this highest dose would be altered by varying the incremental values of the PI schedule (PI 20 s, PI 60 s, and PI 100 s). It seemed plausible that the larger incremental values would be more sensitive to drug-produced disruption because of the increased difficulty in tracking the longer interval lengths.

METHOD

Subjects and Apparatus

Three male subjects participated in this experiment. Two were experimentally naive (S-784 and S-794), and the other (S-453) had served previously in a tobacco-cigarette smoking study several years earlier. This group's mean age was 23 years (range, 18 to to 25 years), their mean number of years of education was 12 (range, 12 to 13), their mean body weight was 80 kg (range, 70 to 90 kg), and their mean reported frequency of marijuana use was less than one occasion per month (range, 0.25 to 1.0 occasions). All had reported using marijuana during the previous 6 months. Subjects reported previous experience with a number of other drugs, including opiates, narcotics, LSD, and benzodiazepines. This group of subjects consisted of 1 African American, 1 Hispanic, and 1 Caucasian.

The apparatus was the same as that used in Experiments 1 and 2.

Procedure

The general screening criteria and testing procedures were similar to those used in Experiment 2, with two exceptions. First, because subjects either smoked the highest dose (3.58% w/w Δ-9-THC) or placebo (0.0001% w/w Δ-9-THC), cigarettes were not cut in half. Second, each subject experienced three arithmetic PI schedules, PI 20 s, PI 60 s, and PI 100 s (in this order of exposure). Each subject began with the arithmetic PI 20-s schedule and was studied for a minimum of 20 sessions before being given an active dose of marijuana. After responding under the PI 20-s schedule stabilized, an active cigarette was administered using the same procedures and criteria used in Experiment 2. On the day following an active dose, the schedule value was altered, and responding was permitted to restabilize before administering another active dose. This sequence was repeated until each subject experienced an active dose at each of the three schedule conditions.

RESULTS

PRPs and rates of responding for all 3 subjects and for all three schedules appear in Figure 6. Each bar in the PRP graph represents the total number of minutes spent in PRPs

Table 3

Subjects' (in Experiments 2 and 3) heart rates (beats per minute) taken before and after smoking either an active or placebo marijuana cigarette and subjective ratings taken after smoking.

Experiment	Subject	% w/w marijuana	Subjective measures				Heart rate (beats per minute)		
			Feel effects	Heart pounding	Feel dizzy	Feel high	Before	After	Change
2	S-877	placebo	1	1	0	0	74	83	+9
		½(1.77)	1	0	1	1	70	104	+34
		1.77	1	1	0	1	74	107	+33
		3.58	2	2	4	3	84	115	+31
	S-880	placebo	0	0	1	0	61	69	+8
		½(1.77)	2	2	1	1	70	82	+12
		1.77	2	3	1	2	65	131	+66
		3.58	3	3	0	3	61	122	+61
	S-915	placebo	0	0	0	0	66	65	−1
		½(1.77)	0	0	0	0	70	89	+19
		1.77	1	0	1	1	72	103	+31
		3.58	1	2	2	1	73	106	+33
3	S-453	placebo	0	1	1	0	63	77	+14
		3.58	1	2	1	1	61	91	+30
		3.58	3	3	2	2	63	110	+47
		3.58	3	4	3	1	68	91	+23
	S-784	placebo	2	1	0	2	67	74	+7
		3.58	2	1	0	2	57	89	+32
		3.58	2	2	0	3	62	87	+25
		3.58	2	1	0	3	53	83	+25
	S-794	placebo	2	1	2	2	80	63	−17
		3.58	3	2	3	4	57	132	+75
		3.58	3	3	4	4	91	140	+49
		3.58	4	4	4	4	92	107	+15

within a session; each bar in the response-rate graph represents the responses (per minute) made during the PI components of the schedule within a session. These measures were calculated using the second session of the day (session following smoking marijuana). The placebo data were taken from the day immediately preceding an active-dose administration day (second session). After smoking an active dose of marijuana, rates of responding increased and PRPs decreased. There was not, however, an obvious effect of schedule length: PRPs did not decrease disproportionately as the schedule's length became greater (e.g., from PI 20 s to PI 100 s).

Rates of responding in the FI component of the schedule varied across subjects following both placebo and active-dose cigarettes, and no systematic effects were observed.

Subjective Measures and Heart Rates

As in Experiment 2, ratings of marijuana effects and heart rates increased more after smoking the active cigarette than the placebo cigarette. These results appear in Table 3.

DISCUSSION

The present study extended PI schedule responding to humans and characterized the effects of smoked marijuana on PI responding. From these experiments, it appears that human responding is similar in some respects to nonhuman PI responding. In rats, pigeons, and humans, PRPs increase in response to the changing temporal requirements, and response rates become very low (see Harzem, 1969; Innis & Staddon, 1971). The few responses that do occur are typically emitted near the end of the PI's temporal requirement. It is worth noting, however, that it required many hours of exposure for responding to stabilize in our experiments. In most cases, responding began at high rates and decreased to low rates only gradually; stabilization normally occurred by the 20th session (a total of 4 days exposure),

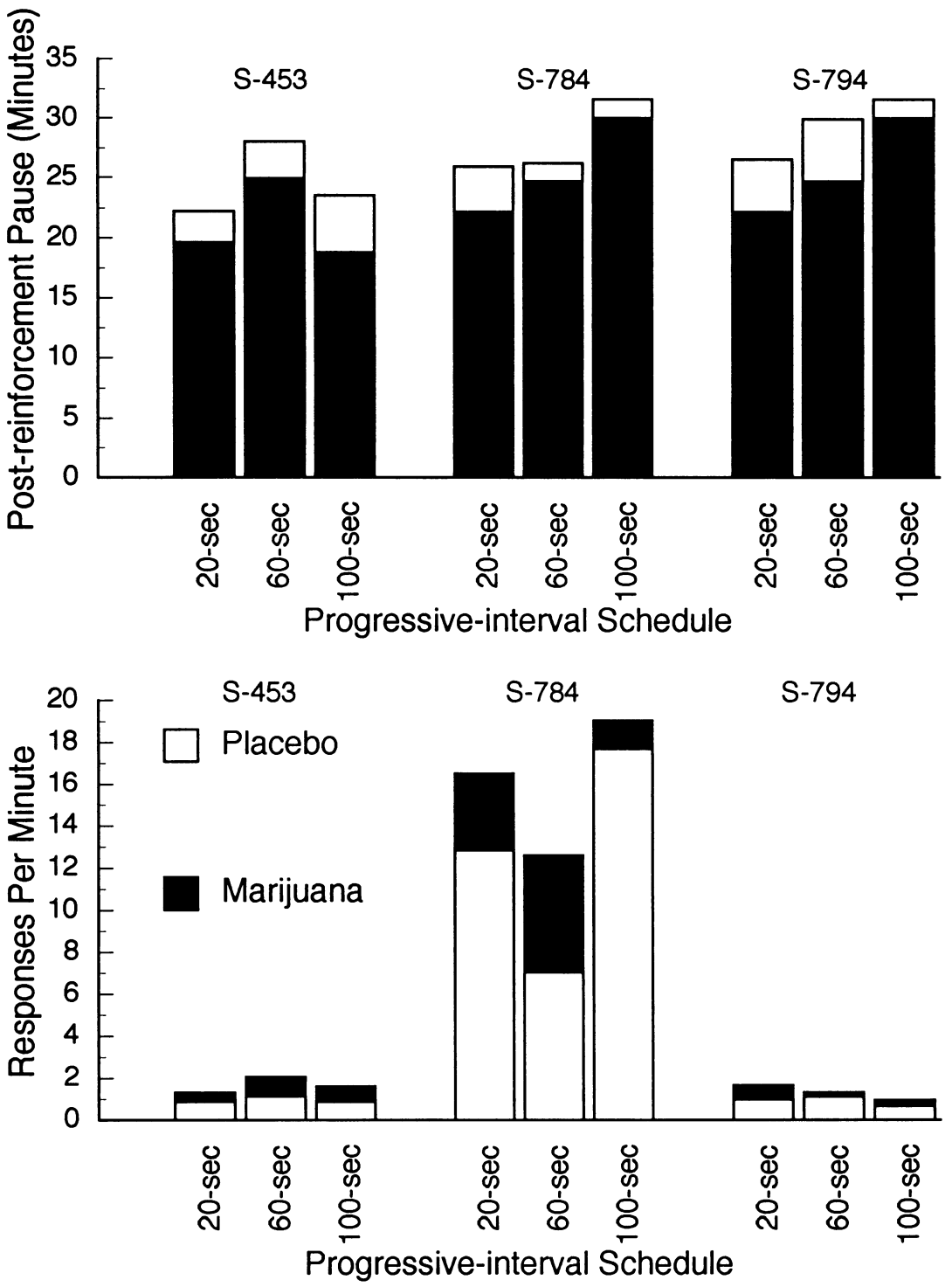

Fig. 6. Three subjects' PRPs (top panel) and responses per minute (bottom panel) after smoking either a high dose of marijuana or a placebo. In the PRP figure, each bar represents the total of all PRPs within a session. In the response-rate figure, each bar represents the responses per minute made in the PI component within a session. The bars are overlaid.

the minimum exposure length under each schedule.

The effects of marijuana (in Experiments 2 and 3) on PI schedule performance are similar in some respects to what has been found after marijuana administration under another time-based schedule that maintains low rates of responding, the differential-reinforcement-of-low-rate (DRL) schedule. Under both PI and DRL schedules, PRPs generally decrease as dose is increased. For example, one study in humans has shown that IRTs under a DRL 20-s limited-hold schedule decrease in a dose-dependent fashion after smoking marijuana (Cappell, Webster, Herring, & Ginsberg, 1972). In that particular study, under placebo conditions, approximately 45% of the nonreinforced responses were shorter than the IRT requirement. After smoking active marijuana cigarettes, the percentage of responses that were shorter than the IRT requirement increased as dose was increased: At the 4-mg, 8-mg, and 16-mg doses, the group's percentage of responses shorter than the IRT requirement was approximately 51%, 54%, and 58%, respectively. This shift toward shorter IRTs under the DRL schedule is similar to the shift toward shorter PRPs that was observed in the present experiments. Similarly, IRT distributions under DRL schedules also become shorter after Δ-9-THC administration in nonhumans. These findings are consistent with the many experimental and subjective reports indicating that humans and nonhumans overestimate the passage of time when they are Δ-9-THC intoxicated (Hicks et al., 1984; Hollister, 1971; Isbel et al., 1967; Jones & Stone, 1970; Mendelson, 1987; Mendhiratta, Wig, & Verma, 1978; Schulze et al., 1989; Tinklenberg et al., 1972).

Response rates under both PI and DRL schedules are also similarly affected by marijuana administration. Low to moderate doses of marijuana elevate baseline response rates (Cole, Pieper, & Rumbaugh, 1971; Manning, 1973, 1976), and high doses of marijuana suppress response rates. Parallel to what is typically observed on DRL schedules, we observed increased rates of responding after subjects smoked active marijuana in Experiments 1 and 2.

The effects of Δ-9-THC under other temporal-based schedules, such as FI and variable-interval (VI) schedules, are also in some ways consistent with what we observed with our subjects under the PI schedules. For example, with both FI (Brady & Balster, 1980; Elsmore & Manning, 1974; Stark & Dews, 1980) and VI schedules (Elsmore & Manning, 1974; Ferraro & Gluck, 1974; Grisham & Ferraro, 1972), low doses of marijuana increased response rates. Yet moderate doses of marijuana have no effect on the temporal distribution of responses on FI schedules (Frankenheim, McMillan, & Harris, 1971). The response rates in our study increased after smoking all doses of marijuana, and the PRPs in the PI component monotonically decreased as dose increased.

In a much broader context, the consistencies observed among individual subjects in this study of human PI responding and its agreement with the nonhuman PI research add to our confidence in the generality of operant contingencies among species. Unlike human FI responding, which often produces a variety of distinctly different patterns of responding (e.g., Duvinsky & Poppen, 1982), the response characteristics under PI schedules appear to be similar among species. In PI schedules, the intervals change according to a pattern. These temporal changes, in effect, lead to consistent schedule-controlled responding. In summary, although there remains considerable debate on the particular role that humans should serve within the experimental analysis of behavior (e.g., Baron, Perone, & Galizio, 1991; Branch, 1991, Dinsmoor, 1991; Pierce & Epling, 1991), it is apparent that orderly schedule-controlled responding can be achieved with PI schedules.

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