JOURNAL OF THE EXPERIMENTAL ANALYSIS OF BEHAVIOR 1989, 52, 111-126 NUMBER 2 (SEPTEMBER)

ORAL SELF-ADMINISTRATION OF PENTOBARBITAL BY RHESUS MONKEYS: MAINTENANCE OF BEHAVIOR BY DIFFERENT CONCURRENTLY AVAILABLE VOLUMES OF DRUG SOLUTION

RICHARD A. MEISCH AND GREGORY A. LEMAIRE

UNIVERSITY OF TEXAS HEALTH SCIENCE CENTER AT HOUSTON

For 4 rhesus monkeys, mouth-contact responses with either of two brass spouts were reinforced according to fixed-ratio schedules by 0.65-mL liquid deliveries during daily 3-hr sessions. Three experiments were conducted. In each experiment, independent fixed-ratio schedules were concurrently in effect at the two spouts. Following completion of each fixed ratio on a spout, a specified number of liquid deliveries were available from that spout under a continuous-reinforcement schedule. The number of such deliveries available at each spout was manipulated independently. In Experiment 1, a 1-mg/mL pentobarbital solution was simultaneously available with water (the drug vehicle) under concurrent fixed-ratio schedules of 32 responses for 3 subjects and 64 responses for the remaining subject. The number (N) of liquid deliveries that were available after completion of each fixed ratio was varied in the following order: 8, 4, 2, 1, and 8 (retest). For each subject at each condition, drug maintained more responding than water. The number of drug deliveries obtained per session was directly related to the amount of drug available per fixed ratio (i.e., to N), whereas the number of fixed ratios completed per session generally was inversely related to the value of N. In Experiment 2, fixed-ratio size was the same for each subject as in Experiment 1, but deliveries of a 1-mg/mL pentobarbital solution were available at both spouts. The number of drug deliveries available under one fixed-ratio schedule (N_s, the "standard" reinforcer amount) was held at eight, and the number of drug deliveries available under the second schedule (N_c, the "comparison" reinforcer amount) was changed across blocks of six sessions of stable responding in the following order: 1, 2, 4, 8, 4, 2, and 1. The identical series of comparison reinforcer amounts (N_c) was then tested twice more, but with the standard reinforcer (N_s) held first at four and then at two deliveries. Across the three choice series, reinforcing effects were directly related to reinforcer magnitude. In Experiment 3, deliveries of a 1-mg/mL pentobarbital solution again were available at both spouts. However, the two reinforcer amounts were held constant at $N = 8$ deliveries under one schedule and $N = 4$ deliveries under the second schedule, and fixed-ratio size was systematically varied. Across the range of fixed-ratio sizes from low to high, the degree to which behavior was better maintained by the larger of the two drug quantities was an inverted U-shaped function of fixed-ratio size. The findings of Experiment 3 are discussed in the context of recent studies that have shown that the relative proportions of behavior maintained by concurrently available reinforcers depend on the absolute values of the concurrent reinforcement conditions, as well as their relative values.

Key words: drug self-administration, oral route, pentobarbital, choice paradigm, reinforcer magnitude, drug volume, concurrent fixed-ratio schedules, mouth-contact responses, rhesus monkeys

When using an orally delivered drug solution as a reinforcer, reinforcer magnitude (i.e., the quantity of drug delivered) can be manipulated either by varying the concentration of drug in a solution or by varying the volume of solution delivered. In addition, the effects on behavior of different drug quantities can be compared across or within sessions. These variables have been examined in a series of experiments with rhesus monkeys in which orally delivered pentobarbital has been available under fixed-ratio (FR) schedules. In three previous experiments, reinforcing effects have been directly related to the quantity of drug delivered. In two of these experiments, drug quantity was manipulated by changing the concentration of drug in a solution, and different drug quantities were available sequentially across sessions (Lemaire & Meisch, 1984) or concurrently within sessions (Meisch & Lemaire, 1988). In a third experiment, in which alcohol as well as pentobarbital was used, drug quantity was manipulated sequentially across

This research was conducted while the authors were at the University of Minnesota and was supported by Grant DA 00944 from the National Institute on Drug Abuse. G. A. Lemaire received support from NIDA Training Grant 5T32 DA07097. We thank John Roache and Peter Silverman for their helpful comments on an earlier version of the manuscript, and Carl Brosman, Rachel Muir, and Chimezie Ukaonu for their assistance in conducting the experiments. Comments and reprint requests may be sent to R. A. Meisch, U. T. Psychiatry-Houston, 1300 Moursund, Houston, Texas 77030.

sessions by changing the number of deliveries of a constant-concentration drug solution that were available following completion of each fixed ratio—that is, by changing the volume of drug solution delivered per fixed ratio (Lemaire & Meisch, 1985). As in the Lemaire and Meisch (1985) experiment, the present study manipulated the volume of a constant-concentration drug solution that was available following completion of each fixed ratio, but it assessed the relative reinforcing effects of different drug quantities by making them concurrently rather than sequentially available.

Three experiments constituted the present study. In an initial experiment, the reinforcing effects of liquid volumes containing one of four pentobarbital quantities were examined in relation to equal volumes of water, the drug vehicle, under concurrent FR FR schedules. The purpose of this first experiment was to examine behavior maintained by each of these drug quantities in isolation before comparing relative amounts of behavior maintained by them when concurrently available.

A second experiment was then conducted in which the four volumes of pentobarbital solution examined in Experiment 1 were systematically made concurrently available with each other, again under concurrent FR FR schedules. A major purpose of Experiment 2 was to attempt to replicate systematically the results of an earlier experiment in which two pentobarbital solutions were concurrently available and drug quantity was manipulated by varying the concentrations of drug in the two solutions (Meisch & Lemaire, 1988); reinforcing effects were directly related to the quantity of pentobarbital delivered in that earlier experiment.

Judgments regarding behavior under concurrent FR FR schedules have been heavily influenced by a few early studies that examined concurrent ratio schedules differing in size, which showed responding to be maintained predominantly under the lower valued schedule, with few crossovers to the second schedule (see, e.g., Catania, 1966). It has perhaps been an implicit assumption that when different reinforcer magnitudes are available under concurrent FR FR schedules, responding will be maintained exclusively by the larger reinforcer amount. The results of a previous experiment in which monkeys orally self-administered different concurrently available pentobarbital concentrations were not inconsistent with this assumption (Meisch & Lemaire, 1988). However, findings pertaining to the maintenance of behavior under concurrent FR FR schedules by two reinforcer amounts have differed across studies and have shown that the degree to which behavior is differentially maintained by two reinforcers is not always as dramatic as might be expected (for studies that have obtained more moderate degrees of differentially maintained behavior, see Collier & Rega, 1971, and Carroll, 1987). Meisch and Lemaire (1988) suggested the possibility that differences between their study and previous studies, in the degree to which behavior was exclusively maintained by the larger of two reinforcer magnitudes, may have been due to differences in the sizes of the FR schedules employed. To investigate this question, a third experiment was conducted in which concurrently available drug-reinforcer amounts were held constant and FR size was systematically manipulated.

GENERAL METHOD

Subjects

Four rhesus monkeys (M-B, M-G2, M-MC, and M-P) served. All subjects participated in each of the three experiments of the study. Monkey M-MC had proceeded through initial procedures to establish pentobarbital as a reinforcer (for a brief description of these procedures, see Lemaire & Meisch, 1985), but was otherwise experimentally naive. Other subjects had participated in several previous oral self-administration experiments involving pentobarbital and/or ethanol: M-B: Lemaire and Meisch (1984); M-G2: DeNoble, Svikis, and Meisch (1982), Lemaire and Meisch (1984), Meisch and Lemaire (1988); M-P: Henningfield and Meisch (1976), Kliner and Meisch (1982), Meisch, Henningfield, and Thompson (1975), Meisch, Kliner, and Henningfield (1981), Meisch and Lemaire (1988).

Mean body weights for Monkeys M-B, M-G2, M-MC, and M-P during the course of the three experiments were 8.6, 9.4, 9.2, and 9.3 kg, respectively, which were 75, 76, 88, and 78% of their free-feeding weights. Unlimited access to food under laboratory conditions, in which lifestyles are relatively sedentary, is not equivalent to free-feeding conditions in the wild, and subjects gain ex-

cessive weight under free-feeding laboratory conditions. This problem is widely recognized; for this reason one pair of investigators maintained pigtail monkeys living in groups of five on "full rations" of 20 g of food per kg of group body weight per day rather than under free-feeding conditions (Crowley & Andrews, 1987, p. 197). Another study reported using "free-feeding" conditions; however, the 9 rhesus monkeys received 150 to 200 g of food per day, divided into one small meal before the session and one large meal after (Grant & Johanson, 1988, p. 780). The free-feeding weights of the present subjects were determined under conditions of unlimited access to food. Under conditions of unlimited food availability 24 hr per day, 2 rhesus monkeys in one study consumed 285 and 295 g daily (Carroll, 1988), and in another study in which unlimited food was available 19 hr per day, 4 rhesus monkeys consumed 255, 258, 268, and 313 g daily (Kliner & Meisch, 1989). The percentages of free-feeding laboratory weights reported for subjects in the present experiments do not represent drastic reductions in weight below a nonobese state. Subjects are healthy in body and behavior at these weights. With monkeys, as with other organisms, there are individual differences in physique and daily caloric utilization; daily food provisions during the present study for the 4 monkeys, in the order listed above, were 120, 190, 160, and 125 g. The rationale for limiting daily food intake is that self-administration of many drugs is increased in laboratory subjects when food intake is limited (for a review, see Carroll & Meisch, 1984). Subjects were monitored daily by veterinary-care staff and were housed under conditions meeting guidelines set by the American Association for the Accreditation of Laboratory Animal Care.

Apparatus

Apparatus was the same throughout the three experiments. Each subject lived continuously in a stainless steel primate cage (Hoeltge, No. HB-108), whose dimensions were 77 by 76 by 100 cm. Three of the cage's walls were solid, and the front wall was barred. Liquids were contained in two covered reservoirs mounted outside the cage in an elevated position. Inside the cage, on one of the side walls, two brass spouts were positioned 52 cm above the cage floor and 15.5 cm to the left and right of the wall's center. The operant response in all three experiments was a mouth contact (either a lip or a tongue contact) with either spout. Electronic drinkometer circuitry in an enclosed casing at the rear of the spout, outside the cage, controlled activation of a solenoid-operated valve that limited liquid flow. When activated by control equipment, this valve allowed an average of 0.65 mL of liquid per delivery to pass from a reservoir, through the spout, and into a monkey's mouth (for a description of the drinking-device apparatus, see Henningfield & Meisch, 1976; for a description of typical response topographies, see Lemaire & Meisch, 1985). A 2.8-W discriminative simulus light, covered with a green jewel lens, was situated 12 cm directly above each spout. Each spout was embedded in a Plexiglas disk, behind which were located four 1.1-W lights, each lying 3 cm from the spout itself, distributed evenly surrounding the spout in an X pattern. Of these four spout lights (which were visible from within the cage), the two that lay on one diagonal of the X were capped with green translucent lenses; the two that lay on the opposite diagonal had white lenses. Programming of contingencies and registration of data were controlled by solid-state equipment (Coulbourn Instruments, Inc.) located in an adjacent room.

General Procedure

Certain procedures were common across the three experiments and are described in this section. The general experimental procedures followed in our laboratory have been described before (e.g., Lemaire & Meisch, 1984, 1985). Briefly, 3-hr experimental sessions were conducted 7 days a week, beginning at 10:00 a.m. Immediately before and after sessions, a 1-hr timeout (TO) period was in effect during which data were recorded, liquids in reservoirs changed, and control equipment appropriately adjusted. Subjects received daily rations of Purina® High Protein Monkey Chow 2 hr after the end of the experimental session. During the intersession period when TO periods were not in effect, water was available from one of the two spouts under an FR-1 schedule, and the 2.8-W discriminative-stimulus light above that spout was illuminated steadily. Responses on the water spout during this time activated its white pair of 1.1-W spout lights for the duration of each mouth-contact response. During sessions, the discriminative-stimulus lights above both spouts flickered at

a rate of 10 Hz, and responses on either spout activated its green pair of spout lights for the duration of each mouth-contact response. General illumination of the monkey room was on a 12:12-hr light/dark cycle (lights on at 6:00 a.m.).

Drug

Sodium pentobarbital was mixed with tap water to form concentrated stock solutions (6.25 mg/mL), which were stored at 3 °C. Two hours before each session, the stock solution was further diluted with tap water to form daily drug solutions. Drug concentrations refer to the salt.

EXPERIMENT 1

In Experiment 1, four different volumes of a pentobarbital solution were concurrently available with identical volumes of the drug vehicle, water. The purpose of this initial experiment was to demonstrate that each of the four quantities of drug (i.e., reinforcer magnitudes) would itself maintain behavior prior to being made concurrently available with other drug quantities in the two subsequent experiments.

Method

The basic reinforcement schedule employed in all three experiments was a tandem (tand) FR-X CRF-N schedule. Under this schedule, completion of an FR requirement of X responses with a spout altered the contingencies to a continuous-reinforcement (CRF) schedule, with no accompanying change in exteroceptive stimulus conditions, under which each of the next N responses resulted in a liquid delivery. Following the Nth reinforcer delivery in the CRF component, the FR component was immediately reinstated—again, with no change in stimulus conditions. Further liquid deliveries were then unavailable until the fixed-ratio response requirement was again satisfied. Thus, reinforcer magnitude was manipulated by altering the number (N) of liquid deliveries that were available under a CRF schedule following each completion of an FR response requirement. This can be conceptualized as manipulating the volume of the reinforcer solution delivered after each fixed ratio, with the modification that the subject controlled the rate at which the volume was delivered by its rate of responding during CRF components; virtually always, all available liquid deliveries in the CRF components were collected in rapid succession.

Two such tandem schedules were concurrently in effect, one at each spout. These schedules were completely independent of each other throughout the three experiments of the present study—responses under each schedule affected consequences only under that schedule and had no effect on the schedule at the opposite spout. In Experiment 1, water was available from one spout under one schedule; at the opposite spout a 1-mg/mL pentobarbital solution served as the reinforcer under the concurrently operating schedule. The FR schedules that constituted the first components of the drug- and water-delivery schedules were of the same size (concurrent FR 32 schedules were used for M-B, M-MC, and M-P, and FR 64 schedules for M-G2). The number of drug deliveries (N) available in the CRF component that followed completion of each fixed ratio on one schedule always equaled the number of water deliveries (N) that were available following each completed fixed ratio on the concurrently operating schedule. This number was changed, across blocks of six sessions of stable behavior, in the following order: N = 8, 4, 2, 1, and 8 (retest); stability was defined as no increasing or decreasing trend in the numbers of drug or water deliveries. Thus the reinforcement contingencies were: concurrent tand FR-X CRF-N (water) tand FR-X CRF-N (drug). The sides at which the two schedules were in effect alternated daily, and thus within the blocks of six sessions at each condition used for data-analysis purposes, drug was available for three sessions at the left spout and for three at the right.

Results

For all three experiments, the data reported are means of the final six sessions at each condition, the sessions that fulfilled the criterion for stable behavior. Table 1 lists the total number of sessions for each subject at each condition and the mean numbers of fixed ratios that were completed at each CRF-N value. Each drug-reinforcer amount (CRF-1, -2, -4, and -8) maintained each subject's behavior well when concurrently available with an identical amount of water: For each subject, the number

Table 1

Mean numbers[a] of fixed ratios completed, numbers of liquid deliveries obtained, and drug intake (mg pentobarbital/kg body weight/3-hr session) at each CRF-*N* value in Experiment 1.

	No. of deliveries per FR	Sessions	Mean FR's completed		Mean deliveries (±*SEM*)		Drug intake
			Drug	Water	Drug	Water	
M-B	8	10	27.2	11.0	217.3 (17.9)	88.0 (35.6)	16.4
(FR 32)	4	6	53.3	11.5	213.2 (10.7)	46.0 (12.3)	16.1
	2	7	55.2	8.7	110.3 (8.5)	17.3 (3.0)	8.3
	1	11	61.3	13.0	61.3 (5.0)	13.0 (3.2)	4.6
	8 (retest)	11	28.4	8.5	226.7 (18.1)	68.0 (21.1)	17.1
M-G2	8	7	37.3	1.6	295.8 (15.9)	11.7 (5.0)	20.5
(FR 64)	4	7	39.8	1.2	159.3 (5.7)	4.7 (2.1)	11.0
	2	10	68.9	1.4	137.5 (12.8)	2.7 (0.9)	9.5
	1	7	58.2	1.2	58.2 (9.4)	1.2 (0.2)	4.0
	8 (retest)	7	30.6	0.9	243.3 (17.0)	6.2 (2.7)	16.8
M-MC	8	6	34.2	2.5	269.7 (6.6)	16.0 (6.0)	19.1
(FR 32)	4	9	48.2	0.8	192.7 (9.4)	3.3 (1.4)	13.6
	2	7	56.5	2.0	113.0 (32.9)	3.7 (1.5)	8.0
	1	12	21.3	1.8	21.3 (10.4)	1.8 (1.0)	1.5
	8 (retest)	6	33.0	1.0	261.8 (12.0)	6.7 (1.5)	18.5
M-P	8	7	47.3	3.3	376.0 (20.7)	25.2 (7.7)	26.3
(FR 32)	4	7	72.3	4.5	287.3 (7.0)	17.3 (2.9)	20.1
	2	9	97.4	2.2	193.7 (8.8)	4.0 (1.1)	13.5
	1	9	119.5	0.6	119.5 (18.3)	0.5 (0.2)	8.4
	8 (retest)	10	48.9	2.7	390.7 (22.0)	21.3 (7.7)	27.3

[a] For this table and subsequent tables and figures, means were calculated for the final six sessions of stable behavior at each condition.

of fixed ratios completed under the water-delivery schedule was much lower than the number completed under the drug schedule, and was not systematically related to CRF-*N* value (Table 1). The number of drug-reinforced fixed ratios completed per session was inversely related to reinforcer magnitude (CRF-*N* value) for Subjects M-B and M-P. For the other 2 subjects (M-G2 and M-MC), the number of drug-reinforced fixed ratios completed can be described as an inverted U-shaped function of reinforcer magnitude—the number completed was greater at CRF-2 than at CRF-1, but thereafter was inversely related to reinforcer magnitude.

Fixed-ratio size remained constant throughout Experiment 1, and therefore the number of drug-maintained responses was nearly always a fixed multiple (64 for M-G2, 32 for the other subjects) of the number of drug-reinforced fixed ratios completed (it was occasionally fractionally higher due to an incompleted ratio at the end of a session). Therefore, overall response rate maintained by drug deliveries was related to reinforcer magnitude for each subject in the same way as was the number of fixed ratios completed. Each subject's drug-maintained responding conformed to the "break and run" pattern typical of responding maintained under FR schedules.

The mean number of pentobarbital deliveries per session was directly related to CRF-*N* value. Because of this, drug intake (mg of pentobarbital per kg of body weight per 3-hr session) was also directly related to CRF-*N* value (Table 1).

Discussion

Experiment 1 served as a necessary control experiment prior to conducting Experiments 2 and 3: It demonstrated that each pentobarbital quantity to be used in the subsequent two experiments (one, two, four, and eight deliveries of a 1-mg/mL pentobarbital solution) served as a reinforcer for each subject, in that it maintained greater amounts of behavior than the concurrently available water vehicle. The greater number of fixed ratios completed under the drug-delivering schedules was due specifically to the presence of the drug and not to nonspecific liquid intake (if nonspecific liquid intake were responsible for the results, it would

be expected that responding would be fairly equally maintained by each available liquid, drug and water).

The use of the number of fixed ratios completed as a dependent variable requires comment. The number of liquid deliveries offered after each fixed ratio differed across CRF-N conditions, and thus the numbers of liquid deliveries obtained per session are not easily compared across reinforcer conditions. The number of liquid deliveries obtained at different reinforcer magnitudes was a direct multiple of the number of fixed ratios completed, being either one, two, four, or eight times the number of completed fixed ratios, depending on the value of CRF-N. The number of fixed ratios completed across reinforcer magnitudes better describes the amount of behavior maintained by each drug amount; therefore, this was the critical dependent variable examined in Experiment 1 and the subsequent two experiments.

Results obtained in Experiment 1 can be compared with those of two previous, related studies that used procedures for varying reinforcer magnitude similar to those of the present study (Kliner, Lemaire, & Meisch, 1988; Lemaire & Meisch, 1985). The mean number of reinforcer deliveries per session increased with CRF-N value in Experiment 1 and in the previous two studies. More complex, however, was the relationship between reinforcer magnitude and the number of fixed ratios completed per session (and thus overall response rate). In Experiment 1, the number of fixed ratios completed and overall response rate were inverted U-shaped functions of reinforcer magnitude for 2 subjects and an inverse function of reinforcer magnitude for the other 2 subjects. Similar heterogeneous results were present in the Lemaire and Meisch (1985) experiment and between Experiments 2 and 3 of the Kliner et al. (1988) study. However, within Experiment 3 of the Kliner et al. study, overall response rate was consistently related to reinforcer magnitude in an inverted U-shaped manner. Under FR schedules, deviations from an inverted U-shaped relation between overall response rate and reinforcer magnitude are probably a consequence of particular parameter values employed rather than of an absence of order between these variables (see Kliner et al., 1988).

EXPERIMENT 2

The purpose of Experiment 2 was to examine the reinforcing effects of specific quantities of pentobarbital when other pentobarbital quantities were simultaneously available. As in Experiment 1, drug quantity was manipulated by varying the number of deliveries of a pentobarbital solution of uniform concentration.

METHOD

In Experiment 2, the same concurrently operating tandem schedules were used as in Experiment 1, but with the following two differences: Pentobarbital solutions (1 mg/mL) served as reinforcers under *both* schedules, and the number of liquid deliveries available following completion of each fixed ratio under the two schedules was separately and independently manipulated. Fixed-ratio sizes in the first components of the concurrent tandem schedules were identical and were the same for each monkey as in Experiment 1.

At one spout, following completion of each fixed ratio a standard number (N_s) of drug deliveries were available under a CRF schedule (a tand FR-X CRF-N_s schedule). Initially, N_s was held constant at eight deliveries. At the second spout, following completion of each fixed ratio a comparison number (N_c) of drug deliveries were available under a CRF schedule (a tand FR-X CRF-N_c schedule). The value of N_c was changed, across blocks of six sessions of stable behavior, in the following order: 1, 2, 4, 8, 4, 2, 1 (the condition in which CRF-N_c was equal to eight was tested only once, for this value was at the turning point in the ascending–descending test sequence of comparison drug quantities). As in Experiment 1, stability was defined as no increasing or decreasing trend in the number of deliveries of either solution. The series of comparison drug quantities began with an ascending rather than descending progression (i.e., N_c began at one delivery and proceeded to eight deliveries, rather than in the reverse order) to maximize initial differences between reinforcer conditions ($N_s = 8$, $N_c = 1$). The sides at which the standard (N_s) and comparison (N_c) quantities were available were reversed daily.

Following completion of the series of comparisons with a standard of eight CRF drug deliveries, the standard was changed to four

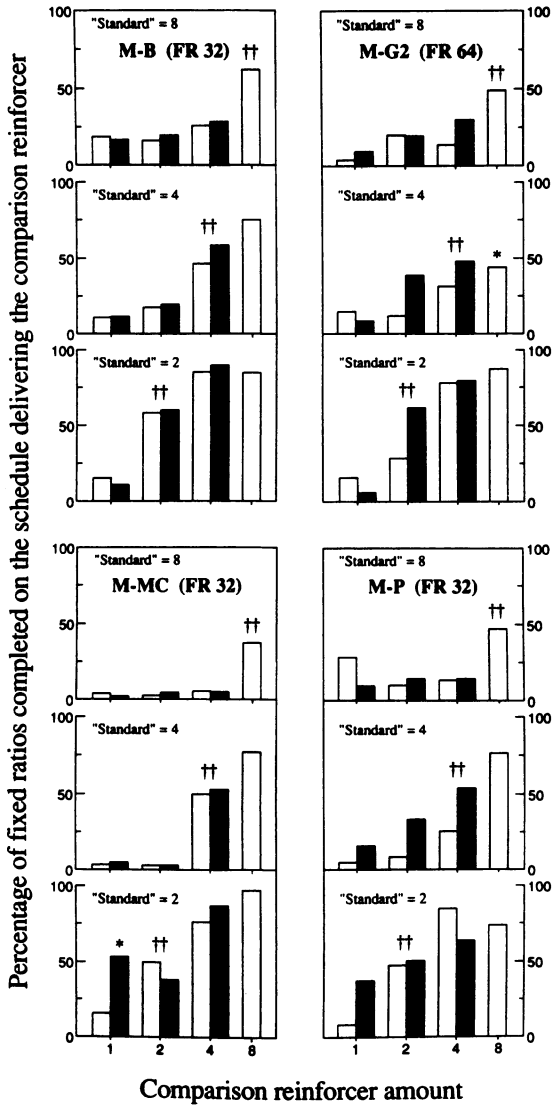

Fig. 1. Bars at each condition represent mean numbers (n = 6) of fixed ratios completed in Experiment 2 on the schedule under which the comparison drug amount was available, as a percentage of the total number of fixed ratios completed at that condition (the number completed on the schedule delivering the standard amount plus the number completed on the schedule delivering the comparison amount). For example, a bar reaching exactly to the 50% level indicates that half of the total number of fixed ratios completed were completed on the schedule delivering the comparison amount, and thus that behavior was maintained equally by the comparison and standard reinforcer amounts. Light and dark bars represent these percentages during the ascending and descending series of comparison (N_c) values, respectively. The comparison condition in which N_c = 8 was tested only once in the series at each standard amount because this value was at the turning point between the ascending and descending series of N_c values. Double daggers appear above conditions in which equal numbers of deliveries were available as the standard and comparison reinforcers. For an explanation of asterisks, see text.

deliveries (i.e., N_s = 4). The same series of comparison (CRF-N_c) values was tested at this four-delivery standard as had been tested at the eight-delivery standard. Finally, following completion of the CRF-N_c series with the CRF-4 standard, the standard was changed to two deliveries (i.e., N_s = 2). The same series of CRF-N_c comparison values was tested at this two-delivery standard as had been tested with the eight- and four-delivery standards. A series was not conducted with a standard of CRF-N_s = 1 because in the earlier series the CRF-1 value was repeatedly tested in comparisons with other CRF-N values.

In each of the three comparison series, there were conditions in which the same volume of drug solution was available under both concurrently operating schedules (viz., when N_s and N_c = 8, N_s and N_c = 4, and N_s and N_c = 2, in the first, second, and third series, respectively). For these conditions, designation of which was the standard and which the comparison drug volume was determined in the following manner: For Subjects M-B and M-G2, beginning on the left side on the first of the six consecutive sessions that formed the block of stable sessions, the drug solution available at alternating sides was termed the standard volume. Thus the mean of the number of deliveries obtained on the left (L), right (R), L, R, L, and R sides over the six sessions was termed the mean number of deliveries obtained under the schedule delivering the standard drug volume. Conversely, the mean number of deliveries obtained on alternating sides beginning with the right side on the first of the same six sessions (i.e., R, L, R, L, R, and L) was termed the mean number of deliveries obtained under the schedule delivering the comparison drug volume. For Subjects M-MC and M-P, the same procedure was applied, but alternation of sides for the standard volume began with the right side on the first session and for the comparison volume on the left side. This procedure was followed to maintain comparability of data analysis with other test conditions, in which particular drug volumes reversed sides daily.

Table 2

Mean numbers (n = 6) of drug deliveries ($\pm SEM$) obtained under the schedules delivering standard (N_s) and comparison (N_c) drug amounts in Experiment 2.

	N_c value	Sessions	N_s = 8	N_c	N_c value	Sessions	N_s = 4	N_c
M-B	1	7	283.8 (17.6)	8.0 (1.2)	1	6	284.0 (5.0)	8.7 (1.4)
(FR 32)	2	8	296.0 (8.8)	14.0 (3.0)	2	6	238.5 (8.7)	25.3 (2.9)
	4	13	258.2 (8.3)	45.3 (7.4)	4	6	156.3 (49.2)	135.3 (53.7)
	8	6	118.5 (24.3)	193.2 (28.5)	8	8	48.7 (8.6)	294.7 (10.2)
	4	6	266.7 (16.5)	52.5 (14.1)	4	7	121.3 (18.9)	172.5 (15.3)
	2	6	312.0 (16.0)	18.7 (3.2)	2	6	256.5 (11.0)	30.7 (9.9)
	1	6	313.3 (4.8)	7.8 (0.7)	1	6	279.3 (10.0)	8.8 (1.8)
M-G2	1	6	412.8 (3.8)	2.2 (1.0)	1	6	277.0 (7.1)	11.7 (3.4)
(FR 64)	2	9	371.5 (22.3)	23.0 (13.9)	2	8	238.5 (17.9)	15.7 (6.9)
	4	6	381.8 (7.3)	30.0 (2.7)	4	7	202.3 (35.8)	91.0 (40.8)
	8	6	206.7 (56.5)	196.0 (61.2)	8	8	120.0 (35.4)	188.8 (39.4)
	4	13	322.8 (24.6)	68.7 (24.1)	4	6	143.3 (45.0)	131.3 (48.3)
	2	7	330.8 (23.4)	20.0 (14.8)	2	14	195.3 (42.3)	60.7 (29.5)
	1	6	334.2 (8.6)	4.3 (1.2)	1	10	271.3 (4.7)	6.2 (1.7)
M-MC	1	6	222.5 (3.7)	1.1 (0.5)	1	11	144.7 (8.0)	1.3 (0.8)
(FR 32)	2	6	218.5 (9.8)	1.3 (0.4)	2	10	142.0 (8.7)	2.0 (1.0)
	4	6	189.3 (4.0)	5.3 (2.2)	4	6	81.3 (36.4)	80.0 (35.8)
	8	6	137.3 (43.9)	81.2 (48.9)	8	12	28.7 (24.0)	194.5 (34.4)
	4	6	213.3 (8.7)	5.3 (2.7)	4	9	85.3 (37.6)	94.0 (35.0)
	2	6	232.0 (25.9)	2.7 (1.1)	2	9	180.7 (11.7)	2.7 (1.3)
	1	6	214.7 (15.7)	0.5 (0.2)	1	7	145.3 (4.8)	1.8 (1.1)
M-P	1	6	258.7 (15.4)	12.7 (7.6)	1	7	261.8 (13.2)	3.3 (0.5)
(FR 32)	2	7	306.7 (15.4)	8.2 (2.7)	2	12	177.8 (7.0)	7.7 (2.2)
	4	9	325.3 (22.6)	25.2 (8.1)	4	7	182.7 (29.7)	62.0 (26.0)
	8	9	193.3 (43.4)	172.0 (39.1)	8	6	43.3 (5.2)	285.2 (18.4)
	4	7	320.0 (6.5)	26.3 (7.4)	4	6	132.0 (25.1)	152.5 (21.5)
	2	7	397.3 (13.8)	16.3 (4.5)	2	9	156.7 (8.5)	39.2 (3.7)
	1	6	385.3 (23.3)	4.8 (1.3)	1	11	188.7 (14.9)	8.8 (3.1)

Results

For each condition, Figure 1 shows the number of fixed ratios completed on the schedule delivering the comparison reinforcer as a percentage of the total number of ratios completed (comparison plus standard) at that condition. Across the series with CRF-8, -4, and -2 standard reinforcer volumes, the number of fixed ratios completed on the schedule delivering the comparison volume was generally a low percentage of the total number completed at a condition when the comparison volume was less than the standard volume and a high percentage of the total number when the comparison volume was greater than the standard volume. In 62 of the 64 conditions in which unequal drug amounts were present (16 conditions per subject, times 4 subjects), the number of fixed ratios completed on the schedule delivering the larger reinforcer exceeded the number completed on the schedule delivering the smaller reinforcer. The two exceptions occurred when side preferences developed at conditions in which reinforcer amounts differed only by a factor of two (as marked by asterisks in Figure 1, these instances were with M-G2 at $N_s = 4$ and $N_c = 8$, and with M-MC at the retest of $N_s = 2$ and $N_c = 1$). At each standard reinforcer amount, results generally were qualitatively similar during the ascending and descending series of comparison reinforcer amounts.

At conditions in which the values of CRF-N_s and CRF-N_c were equal, there was no systematic tendency for a greater percentage of fixed ratios to be completed on either the schedule under which the "standard" or "comparison" pentobarbital quantities were available. However, this equal maintenance of behavior by the standard and comparison drug amounts usually did not result from responding being equally distributed between the left and right spouts; rather, side preferences (or side biases) almost always developed under these equal-reinforcer conditions: Across sessions, subjects

Table 2
(*Continued*)

N_c value	Sessions	$N_s = 2$	N_c
1	6	213.7 (3.8)	19.2 (4.9)
2	6	94.0 (24.8)	129.3 (20.7)
4	9	22.0 (6.3)	256.7 (9.7)
8	6	15.0 (2.1)	333.2 (3.9)
4	7	17.0 (5.7)	290.7 (12.3)
2	6	89.7 (24.9)	134.0 (25.6)
1	6	186.0 (7.0)	11.2 (2.1)
1	6	186.3 (7.3)	6.8 (1.6)
2	6	124.8 (13.4)	48.7 (16.0)
4	15	30.3 (17.2)	218.5 (32.4)
8	6	13.0 (9.2)	350.2 (7.8)
4	9	30.7 (17.6)	241.3 (21.8)
2	6	81.0 (24.1)	129.8 (24.5)
1	6	182.0 (7.6)	5.8 (1.3)
1	17	73.0 (17.7)	6.7 (6.1)
2	6	53.0 (23.8)	52.7 (23.6)
4	7	19.7 (15.1)	131.2 (29.3)
8	10	2.0 (0.9)	278.3 (8.1)
4	8	11.3 (7.9)	156.5 (22.0)
2	6	75.7 (35.4)	46.8 (20.7)
1	10	65.3 (29.4)	37.0 (17.1)
1	11	128.3 (12.6)	5.8 (0.5)
2	6	49.0 (15.9)	43.8 (18.3)
4	9	14.0 (4.3)	157.3 (11.7)
8	10	24.3 (10.5)	272.0 (19.3)
4	10	44.3 (19.9)	152.7 (33.6)
2	6	54.7 (25.0)	55.7 (23.2)
1	9	114.0 (19.6)	33.3 (20.3)

responded predominantly or exclusively on one-and-the-same spout. Under these conditions the drug amount available from a particular spout was termed standard one session and comparison the next (see above), and therefore the percentages of fixed-ratio completions maintained by the standard and comparison drug amounts across the six stable sessions were fairly equal—the result of averaging three high values (from the preferred side) with three low ones (from the nonpreferred side). Mild side preferences also were occasionally evident with each subject at various conditions in which reinforcer amounts were unequal: The standard or comparison amounts, or both, maintained more responding when present on one side than on the other. However, with the two exceptions noted above, the presence of a side preference did not interfere with the larger drug amount maintaining more fixed-ratio completions.

Across all conditions, each monkey obtained greater numbers of drug deliveries per session on the schedule under which the larger number of deliveries were available than on the schedule under which the smaller number were available (Table 2). At conditions in which equal numbers of deliveries were available following completion of a response ratio on either schedule (i.e., when both CRF-N_s and CRF-N_c equaled eight, four, or two deliveries), fairly equivalent numbers of drug deliveries were usually obtained from both schedules due to the side preferences noted above.

Discussion

The results of Experiment 2 systematically replicated those of a previous experiment that had manipulated the quantity of pentobarbital delivered after each fixed ratio by varying the concentration of drug in a solution (Meisch & Lemaire, 1988). The earlier experiment made different drug concentrations concurrently available first with water and then with other drug concentrations, in a design similar to that of the present study. In both the earlier experiment and Experiment 2 of the present study, three different drug amounts served sequentially as a standard reinforcer, and in both experiments the amount of behavior maintained by particular comparison drug amounts was high when the standard reinforcer was a lesser drug amount and low when the standard reinforcer was a greater drug amount.

Although a similar design was used in the earlier (Meisch & Lemaire, 1988) and present studies, the discrimination required between concurrently available reinforcers was very different. In the earlier study, two concurrently available drug solutions differed in concentration but were equal in volume (a single drug delivery followed completion of each fixed ratio). Discrimination between the two available drug quantities most probably was based on taste differences. In the present study, the only difference between drug quantities was the number of deliveries available following completion of response ratios. The most probable bases of discrimination between the two drug quantities were differences in the events accompanying different numbers of drug-solution deliveries. An audible "click" is produced by the mechanical operation of the solenoid controlling liquid flow, and the basis of differential responding may therefore have been differences in numbers of audible clicks, differences in liquid volumes delivered, or both.

The results of Experiment 2 are consistent with previous experiments using concurrent schedules, which have shown responding to be better maintained by the larger of two drug quantities delivered intravenously (e.g., Iglauer & Woods, 1974; Johanson & Schuster, 1975).

EXPERIMENT 3

In Experiment 3, the relation between differential maintenance of responding by two reinforcers and FR size was examined. Concurrently available drug-reinforcer amounts were held constant at eight and four deliveries throughout the experiment, and FR size was systematically manipulated. A 2:1 ratio between reinforcer amounts was selected (rather than, say, a 4:1 or an 8:1 ratio) because it was felt that an influence of FR size on differential maintenance of responding would most likely be manifested, if at all, under conditions in which there was not a large relative difference between reinforcers.

METHOD

In Experiment 3, the same basic concurrent tandem schedule conditions prevailed as in the previous two experiments, but the concurrently available drug-reinforcer amounts were held constant while FR size was systematically varied. Reinforcer amounts were $N = 8$ deliveries of a 1-mg/mL pentobarbital solution under one schedule and $N = 4$ deliveries of an identical solution under the second schedule. As in Experiments 1 and 2, the schedules delivering the different reinforcer amounts (CRF-8 and CRF-4) were concurrently in operation on sides that alternated from one session to the next.

As an initial baseline, subjects were tested at the same FR sizes at which they had been tested in Experiments 1 and 2 (concurrent FR 32 FR 32 for M-B, M-MC, and M-P; concurrent FR 64 FR 64 for M-G2). Following six sessions of stable responding, FR size was doubled (to FR 64 for 3 subjects, and FR 128 for M-G2), and the same pentobarbital quantities (eight and four deliveries) were again concurrently available until a subject's behavior was stable for six sessions. Fixed-ratio size continued to be doubled for each subject, on an individual basis, until either (a) there was a "breakdown" in the greater maintenance of behavior by the large drug quantity (CRF-8), or (b) the number of drug deliveries obtained declined to less than 25% of baseline levels; the latter criterion was established because further doubling FR size when behavior was very weakly maintained might result in the abolition of all drug-maintained responding, with the attendant necessity of instituting a reacquisition procedure. When a subject's behavior met either of these criteria, the subject was not tested at higher FR sizes; rather, a retest was then conducted of all FR sizes tested with that subject in the ascending sequence, but with FR sizes tested in reverse order (i.e., in order of decreasing size).

This descending FR-size series did not halt when the initially tested FR size was reached; rather, FR size continued to be halved in a prolonged series of descending FR sizes. The design of Experiment 3 called for continuing to halve FR size for each subject following six sessions of its stable behavior until either of two criteria was met: (a) differential maintenance of behavior by the larger and smaller reinforcer magnitudes again broke down, or (b) FR 1 was reached. As it happened, the descending series of FR sizes has halted for each subject according to the first criterion (i.e., consistent differential maintenance of behavior by the two reinforcers disappeared for each subject at an FR size above FR 1). For M-B and M-MC, the first criterion was actually met at FR 16 and FR 8, respectively (i.e., behavior maintained by the two reinforcer amounts did not differ to a large extent). These 2 subjects exhibited only fairly moderate side preferences at these FR sizes. However, the other 2 subjects (M-G2 and M-P) each developed strong, nearly exclusive, side preferences at the lowest FR sizes tested in their descending FR-size sequences. We wished to observe whether M-B's and M-MC's side preferences would become more pronounced at a lower FR size; therefore fixed-ratio size was decreased one further step (to FR 8 for M-B and FR 4 for M-MC); this did indeed result in a further exaggeration of the side preferences already present at the previous FR size. Following testing at the lowest FR size in the descending series, a retest of FR sizes in this second series was then conducted for each subject in an ascending order until the original FR size of Experiment 3 was reached for each subject (FR 32 or 64).

Experiment 3 was originally designed to conclude at this point in the procedure. However, M-B's behavior under its original schedule size (FR 32) was not better maintained by the CRF-8 reinforcer. For this subject, therefore, FR size was again doubled once (to FR 64), which resulted in the reestablishment of differential maintenance of behavior, and then halved again, back to the baseline FR-32 condition, at which behavior continued to be better maintained by the CRF-8 reinforcer magnitude; the experiment was then terminated for M-B at this point.

Results

Table 3 lists the mean numbers of drug deliveries obtained by each subject at each FR size tested. Figure 2 shows the major dependent variable, the mean numbers of fixed ratios completed on the schedules under which eight and four deliveries were available. At the initial baseline FR sizes, all 4 subjects completed a greater number of fixed ratios on the eight-delivery schedule than on the four-delivery schedule, though barely so in the case of M-G2. In the ascending FR series, differential maintenance of behavior by the two pentobarbital quantities disappeared either gradually or (in the case of M-G2) rapidly across increases in FR size. Each increase in FR size from the baseline size resulted in a decrease in the number of fixed ratios completed. Conversely, decreases in FR size during the descending FR series resulted in increases in the number of fixed ratios completed. At the lowest FR sizes at which they were tested, M-P consistently consumed amounts of drug sufficient to produce an anesthetic state, and M-B and M-MC consistently consumed amounts producing severe behavioral intoxication.

Differential maintenance of monkeys' responding by the two reinforcer amounts was an inverted U-shaped function of FR size: Superior maintenance of behavior by the larger reinforcer magnitude (CRF-8) was maximal at intermediate FR sizes and less evident or absent altogether at higher and lower FR sizes. There were individual differences in the functions relating differential maintenance of behavior to FR size: Across subjects, differentially maintained behavior disappeared at FR sizes ranging from 128 to 512 responses during the ascending FR series and at FR sizes ranging from 8 to 32 responses during the descending FR series. With 3 of the 4 subjects (M-G2 being the exception), the breakdown in differentially maintained behavior at the highest FR sizes tested in the ascending series was the result of responding being fairly evenly divided between the schedules in effect at the left and right spouts; for M-G2, it was due to the development of a side preference. For all 4 subjects, loss of differentially maintained behavior at the lowest FR sizes tested in the descending FR series was due to development of side preferences.

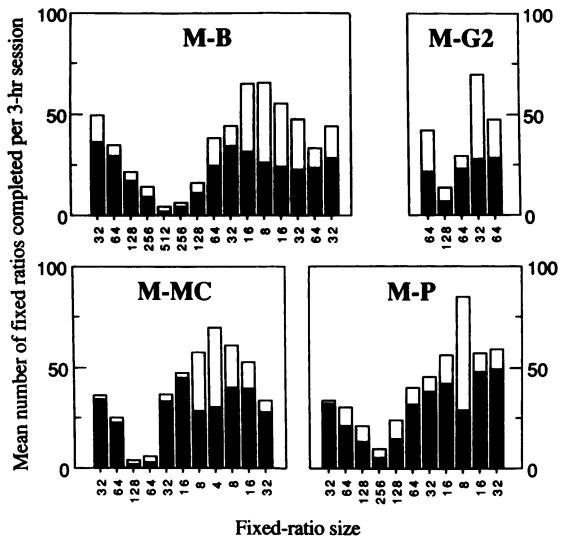

Fig. 2. Dark and light bars at each condition represent mean numbers (n = 6) of fixed ratios completed in Experiment 3 under the schedules delivering the CRF-8 and CRF-4 reinforcer amounts, respectively. Bars are stacked, and the area of each bar therefore represents behavior maintained by only one reinforcer amount without overlap (thus, note that at each condition the number of fixed ratios completed under the schedule delivering the CRF-4 reinforcer is represented solely by the area of the light bar itself and not by the sum of the areas of the light and dark bars). Fixed-ratio sizes are listed along the abscissae in the order in which they were tested for each subject.

Table 4 presents the data from Figure 2 in a different manner. For each of the two reinforcer amounts, the number of fixed ratios completed by each subject at the lowest FR size at which it was tested is set equal to 100%, and the numbers of fixed ratios completed at each higher FR size are expressed as percentages of the number completed at the same reinforcer amount at the lowest FR size. Table 4 shows that with increases in FR size above the lowest one tested, the number of fixed ra-

Table 3

Mean numbers (n = 6) of drug deliveries ($\pm SEM$) at each FR size in Experiment 3.

M-B				M-G2			
FR size	Sessions	N = 8	N = 4	FR size	Sessions	N = 8	N = 4
32	9	290.7 (32.1)	52.0 (28.5)	64	9	173.2 (37.5)	81.8 (20.1)
64	8	233.0 (13.9)	21.3 (4.5)	128	18	54.5 (23.9)	27.3 (8.1)
128	8	138.5 (6.8)	16.7 (4.3)	64	10	184.2 (28.7)	24.0 (17.0)
256	7	71.8 (9.8)	18.7 (2.9)	32	7	224.0 (98.8)	166.7 (75.4)
512	8	13.2 (3.6)	7.3 (1.7)	64	12	226.3 (58.2)	76.5 (43.5)
256	7	34.7 (13.7)	7.2 (3.4)				
128	9	90.7 (11.0)	18.7 (4.3)				
64	11	193.3 (10.0)	56.0 (9.6)				
32	8	272.0 (19.6)	38.7 (16.3)				
16	12	250.7 (56.0)	134.7 (52.7)				
8	7	202.0 (49.0)	157.2 (55.7)				
16	8	189.3 (64.0)	126.0 (61.4)				
32	10	180.0 (44.2)	99.3 (41.1)				
64	6	186.3 (17.5)	38.7 (7.4)				
32	8	225.2 (33.3)	61.3 (26.3)				

tios completed on the schedule delivering the CRF-4 drug amount declined more rapidly than the number completed on the schedule delivering the CRF-8 reinforcer amount, as a percentage of the number completed at the lowest FR size; this effect was independent of whether FR sizes were tested in an ascending or descending order.

Discussion

The FR size manipulations clearly demonstrated that FR size can be an important variable determining the degree to which behavior will be better maintained by the larger of two concurrently available reinforcers. The changes that occurred in responding at both the highest and lowest schedule values involved more than the quantitative differences shown in Figure 2 and Table 3. At the highest FR sizes at which they were tested, most subjects' pattern of responding was markedly altered from what it had been at lower FR sizes. M-P's response pattern during sessions at FR 256 (the highest schedule value at which this subject was tested) typically consisted of short response bursts on one spout (of approximately 5 to 40 responses per burst), followed by switching to the other spout for a short response burst, then switching back to the first spout for another short period of responding, and so on. At FR 256, therefore, this subject's behavior was no longer being differentially maintained by the two reinforcer magnitudes; rather, responding on both spouts was maintained by intermittent drug deliveries from either spout. We did not observe such changeovers during response sequences in Experiment 2 or in a previous experiment in which solutions differing in the concentration of pentobarbital they contained were available under concurrent FR FR schedules of moderate size (Meisch & Lemaire, 1988). For Subjects M-B and M-MC, interruptions and pauses during response sequences characteristic of "ratio strain" were seen when FR sizes were increased to high values.

The factors responsible for the disappearance of differentially maintained responding at the low FR sizes likely were different than those affecting behavior at the high FR sizes. At the lowest FR sizes, a greater number of fixed ratios were completed by each subject under the four- than under the eight-delivery schedule (Figure 2). However, this was not due to the smaller drug quantity better maintaining behavior; that is, subjects did not consistently respond on the schedule under which the CRF-4 reinforcer was available. Rather, the results reflect the striking side preferences present at these low FR sizes. At the low FR sizes, both the larger and smaller reinforcer amounts maintained behavior well; differences between them did not result in different functional effects on behavior. Under such conditions, the effects of less salient variables, such as the variables determining side preference, may control responding.

Table 3
(*Continued*)

M-MC				M-P			
FR size	Sessions	$N = 8$	$N = 4$	FR size	Sessions	$N = 8$	$N = 4$
32	7	274.0 (4.7)	6.7 (2.9)	32	10	256.0 (37.1)	6.7 (8.2)
64	6	180.0 (8.7)	8.0 (4.7)	64	9	169.3 (6.9)	36.0 (2.5)
128	8	10.7 (3.7)	5.3 (1.5)	128	6	105.3 (11.2)	29.8 (5.6)
64	9	20.0 (4.4)	9.3 (1.5)	256	8	38.7 (8.3)	16.7 (7.5)
32	14	264.0 (14.0)	12.7 (3.1)	128	8	117.2 (21.0)	37.3 (11.2)
16	7	357.3 (9.8)	10.7 (1.4)	64	12	255.8 (17.5)	32.7 (6.2)
8	7	227.0 (57.9)	115.8 (65.2)	32	8	303.3 (11.4)	28.7 (11.1)
4	8	243.8 (68.1)	156.2 (68.1)	16	6	336.0 (19.1)	55.3 (24.9)
8	12	311.3 (63.4)	82.2 (56.3)	8	8	225.2 (111.2)	225.8 (108.4)
16	8	312.7 (36.8)	51.5 (25.0)	16	13	375.0 (11.0)	37.3 (10.8)
32	6	220.0 (19.3)	20.8 (3.9)	32	7	392.0 (9.6)	38.0 (10.3)

Experiment 3 in Relation to Other Studies of Behavior in Choice Situations

Findings related to those of Experiment 3 can be found in experiments concerning the matching law. The matching law describes relationships typically observed between relative response rates and relative reinforcement conditions under concurrent schedules. Under concurrent variable-interval (VI) and concurrent-chains schedules, response rates are fairly consistently proportional to differences in the rate, amount, or delay of reinforcer delivery (see, e.g., Davison & McCarthy, 1988). An assumption of the matching law is that relative response rates maintained by concurrently available reinforcers should be a function of relative differences in reinforcement-parameter values but independent of the absolute values of these parameters (cf. Alsop & Elliffe, 1988; Davison & McCarthy, 1988, p. 14; Logue & Chavarro, 1987). However, evidence is accumulating that the relationships described in various forms of the matching law are not universal across all parameter values; rather, it has been demonstrated that relative response rates under concurrent schedules are affected by the absolute values of reinforcement parameters as well as their relative values. Results of Experiment 3 of the present study are relevant to studies using concurrent VI VI or concurrent-chains schedules that either explicitly tested the assumption of the matching law that relative response rates should be independent of absolute reinforcement values (e.g., Alsop & Elliffe, 1988; Davison, 1988; Logue & Chavarro, 1987), or that without having been specifically designed to do so, obtained results violating that assumption (e.g., Ito, 1985; Snyderman, 1983).

Differential maintenance of behavior can also be affected by either increases or decreases in schedule-parameter values. Davison (1988) examined pigeons' responding under nonindependent concurrent VI VI schedules whose mean interval lengths were kept equal to each other but were manipulated together across the range from 16 to 24 s. Unequal reinforcer amounts were available under the two schedules (3 s and 10 s of grain access). Response rates under the two schedules became more even as the absolute frequency of reinforcement increased (i.e., as VI schedule length decreased). These results may be analogous to those of Experiment 3, in which as concurrent FR schedule sizes were decreased to low values, differences in the functional effects upon responding of two reinforcer amounts lessened. (In what may be related phenomenon, Blough, 1966, noted that performance is improved in discrimination paradigms when behavioral requirements are increased.)

Differential maintenance of behavior can also be affected by increases in schedule-parameter values. Logue and Chavarro (1987) examined pigeons' relative response rates under nonindependent concurrent VI VI schedules as the absolute values of several parameters (delay, amount, and frequency of reinforcement) were manipulated while the proportion between parameter values was kept constant at 3:1. As reinforcer frequency decreased across the range of absolute values tested (i.e., as concurrent VI schedule values

Table 4

Mean numbers ($N = 6$) of fixed ratios completed at each FR size in Experiment 3 as percentages of the number completed at the lowest FR size tested.

M-B			M-G2			M-MC			M-P		
FR size	$N = 8$	$N = 4$	FR size	$N = 8$	$N = 4$	FR size	$N = 8$	$N = 4$	FR size	$N = 8$	$N = 4$
32	144	33	64	77	49	32	112	4	32	113	3
64	115	14	128	24	16	64	74	5	64	75	16
128	69	11	64	82	14	128	4	3	128	47	13
256	36	12	32	100[a]	100[a]	64	8	6	256	17	7
512	7	5	64	101	46	32	108	8	128	52	17
256	17	5				16	147	7	64	114	14
128	45	12				8	93	74	32	135	13
64	97	37				4	100[a]	100[a]	16	149	24
32	135	25				8	128	53	8	100[a]	100[a]
16	124	86				16	128	33	16	167	16
8	100[a]	100[a]				32	90	13	32	174	17
16	94	80									
32	89	63									
64	92	25									
32	111[b]	39[b]									

[a] By definition, the numbers of fixed ratios completed at the lowest FR size tested are set equal to 100% for each reinforcer.

[b] For example, the lowest FR size at which Monkey M-B was tested was FR 8, and at this FR size he completed 25.3 and 39.3 fixed ratios under the schedules delivering the CRF-8 and CRF-4 reinforcer amounts, respectively. During the final test at FR 32, M-B completed 28.2 and 15.3 fixed ratios under the schedules delivering these reinforcer amounts, which are 111% and 39% of the numbers completed at FR 8, respectively.

were lengthened), the ratio between response rates under the concurrent schedules became more even. In an earlier experiment that did not maintain a constant proportion between schedule values across conditions, pigeons' preferences for the smaller of two concurrently operating variable-ratio (VR) schedules were investigated (Herrnstein & Loveland, 1975); the magnitude of the difference between VR schedules required to obtain a preference for the smaller schedule increased with increases in the absolute sizes of the schedules. (The authors included a caveat noting that 2-s grain access served as the reinforcer under some conditions and 3-s access under others, but the data are nonetheless consistent with the results obtained with concurrent VI VI schedules: The effects on responding of differences in concurrent reinforcement conditions were lessened as schedule parameters were increased to large values.) In Experiment 3 of the present study, reinforcer amount rather than schedule value differed between concurrent schedules, but a similar decrease in the effects upon behavior of differences between concurrent reinforcement conditions was observed as the sizes of concurrent FR schedules were increased to high values. Taken together, the results of these studies using concurrent VI VI, VR VR, and FR FR schedules suggest the possiblity that, regardless of the basic concurrent schedules involved, a general decrease in the sensitivity of behavior to control by differences in reinforcement conditions may occur as schedule-parameter values are increased to extreme levels. This may involve changes in the discriminability of reinforcement conditions: Although concurrent reinforcement conditions, themselves, can assume discriminative functions (Bourland & Miller, 1981; Davison & McCarthy, 1988, p. 240; Miller, Saunders, & Bourland, 1980), discriminability between conditions is likely diminished when the frequency of reinforcement is decreased to very low rates (cf. Alsop & Elliffe, 1988). The influence of the discriminability of conditions on responding under concurrent schedules has previously received attention (Baum, 1974; Davison & McCarthy, 1988, pp. 80–82, 151).

The studies discussed above demonstrated a more even distribution of responding between concurrently operating schedules as schedule-parameter values were increased, decreased, or both increased and decreased (the evenness

of responding being a U-shaped function of parameter value). Separate processes may be implicated in the relation between independent and dependent variables at different points across a range of parameter values. Recent studies using concurrent schedules have also manipulated the absolute values of reinforcer magnitudes (Logue & Chavarro, 1987; Mazur, 1988) and delays to reinforcement (Logue & Chavarro, 1987) while preserving a constant proportion between concurrent paramter values, and reported that relative preferences between concurrent conditions did not remain constant across these manipulations. Differential maintenance of behavior in choice situations is thus a function both of the relative and absolute values of several reinforcement parameters. The findings of Experiment 3 imply that to characterize fully the relationship of responding in choice situations to each reinforcement parameter, an examination of an extensive range of values of each parameter, from very low to very high, is crucial.

GENERAL DISCUSSION

The present study is one in a series conducted in this laboratory that have examined the relation of drug-self-administration behavior to interactions between FR size and drug-reinforcer magnitude. Reinforcer magnitude in these experiments has been manipulated by varying the concentration of drug in a solution (Lemaire & Meisch, 1984; Meisch & Lemaire, 1988) or the volume of a drug solution whose concentration remained constant (Lemaire & Meisch, 1985; the present study). The results of these studies have been consistent: Reinforcing effects are directly related to drug quantity (i.e., to reinforcer magnitude); this relationship holds when drug quantity is manipulated in either of two ways and when different drug quantities are available either sequentially or concurrently.

Each method of manipulating drug quantity in an orally delivered solution (varying the concentration of drug or varying the volume of solution) has features that potentially can confound interpretation of results. Thus, on the one hand, when the concentration of drug in a solution is altered, so also is the taste of the solution. The possibility therefore arises that results may be due to differences in the reinforcing effects of the gustatory stimulation provided by the different drug solutions rather than to the pharmacological effects of the drug quantities delivered. However, in an earlier report of monkeys' responding maintained by concurrently available pentobarbital solutions differing in concentration, evidence in favor of a pharmacological-effects interpretation and against an interpretation based on taste differences was presented (Meisch & Lemaire, 1988). On the other hand, a potential difficulty arising when the quantity of drug delivered is manipulated by varying the volume of a drug solution is that results may be due to differences in liquid volumes rather than differences in drug quantities. However, this possibility was ruled out as an explanation of the present study's results by the demonstration in Experiment 1 that reinforcing effects were due to the presence of different quantities of pentobarbital rather than to different volumes of liquid. Thus, in general terms, this series of experiments has demonstrated that (a) orally delivered pentobarbital can serve as an effective reinforcer for rhesus monkeys over extensive periods of time, (b) reinforcing effects are directly related to the quantity (in milligrams) of pentobarbital delivered, and (c) the reinforcing effects are not due to experimental artifacts involving the taste or volume of liquid solutions.

These experiments have also shown a congruence between two measures of the reinforcing effects of different drug quantities—relative persistence of responding from baseline levels as FR size is increased (Experiment 3; Lemaire & Meisch, 1984, 1985), and relative rates of responding in a concurrent-choice situation (Experiment 2; Meisch & Lemaire, 1988). According to both measures, reinforcing effects are directly related to drug quantity.

REFERENCES

Alsop, B., & Elliffe, D. (1988). Concurrent-schedule performance: Effects of relative and overall reinforcer delivery rate. *Journal of the Experimental Analysis of Behavior*, **49**, 21–36.

Baum, W. M. (1974). On two types of deviation from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior*, **22**, 231–242.

Blough, D. S. (1966). The study of animal sensory processes by operant methods. In W. K. Honig (Ed.), *Operant behavior: Areas of research and application* (pp. 345–379). New York: Appleton-Century-Crofts.

Bourland, G., & Miller, J. T. (1981). The role of discriminative stimuli in concurrent performances. *Jour-*

nal of the Experimental Analysis of Behavior, **36,** 231–239.

Carroll, M. E. (1987). Concurrent access to two concentrations of orally delivered phencyclidine: Effects of feeding conditions. *Journal of the Experimental Analysis of Behavior,* **47,** 347–362.

Carroll, M. E. (1988). Oral self-administration of N-allylnormetazocine (SKF-10,047) stereoisomers in rhesus monkeys: Substitution during phencyclidine self-administration and withdrawal. *Pharmacology Biochemistry and Behavior,* **30,** 493–500.

Carroll, M. E., & Meisch, R. A. (1984). Increased drug-reinforced behavior due to food deprivation. In T. Thompson, P. B. Dews, & J. E. Barrett (Eds.), *Advances in behavioral pharmacology* (Vol. 4, pp. 47–88). Orlando, FL: Academic Press.

Catania, A. C. (1966). Concurrent operants. In W. K. Honig (Ed.), *Operant behavior: Areas of research and application* (pp. 213–270). New York: Appleton-Century-Crofts.

Collier, G., & Rega, F. (1971). Two-bar sucrose preference. *Learning and Motivation,* **2,** 190–194.

Crowley, T. J., & Andrews, A. E. (1987). Alcoholic-like drinking in simian social groups. *Psychopharmacology,* **92,** 196–205.

Davison, M. (1988). Concurrent schedules: Interaction of reinforcer frequency and reinforcer duration. *Journal of the Experimental Analysis of Behavior,* **49,** 339–349.

Davison, M., & McCarthy, D. (1988). *The matching law: A research review.* Hillsdale, NJ: Erlbaum.

DeNoble, V. J., Svikis, D. S., & Meisch, R. A. (1982). Orally delivered pentobarbital as a reinforcer for rhesus monkeys with concurrent access to water: Effects of concentration, fixed-ratio size, and liquid positions. *Pharmacology Biochemistry and Behavior,* **16,** 113–117.

Grant, K. A., & Johanson, C. E. (1988). Oral ethanol self-administration in free-feeding rhesus monkeys. *Alcoholism: Clinical and Experimental Research,* **12,** 780–784.

Henningfield, J. E., & Meisch, R. A. (1976). Drinking device for rhesus monkeys. *Pharmacology Biochemistry and Behavior,* **4,** 609–610.

Herrnstein, R. J., & Loveland, D. H. (1975). Maximizing and matching on concurrent ratio schedules. *Journal of the Experimental Analysis of Behavior,* **24,** 107–116.

Iglauer, C., & Woods, J. H. (1974). Concurrent performances: Reinforcement by different doses of intravenous cocaine in rhesus monkeys. *Journal of the Experimental Analysis of Behavior,* **22,** 179–196.

Ito, M. (1985). Choice and amount of reinforcement in rats. *Learning and Motivation,* **16,** 95–108.

Johanson, C. E., & Schuster, C. R. (1975). A choice procedure for drug reinforcers: Cocaine and methylphenidate in the rhesus monkey. *Journal of Pharmacology and Experimental Therapeutics,* **193,** 676–688.

Kliner, D. J., Lemaire, G. A., & Meisch, R. A. (1988). Interactive effects of fixed-ratio size and number of food pellets per fixed ratio on rats' food-reinforced behavior. *Psychological Record,* **38,** 121–143.

Kliner, D. J., & Meisch, R. A. (1982). The effects of food deprivation and satiation on oral pentobarbital self-administration in rhesus monkeys. *Pharmacology Biochemistry and Behavior,* **16,** 579–584.

Kliner, D. J., & Meisch, R. A. (1989). Oral pentobarbital intake in rhesus monkeys: Effects of drug concentration under conditions of food deprivation and satiation. *Pharmacology Biochemistry and Behavior,* **32,** 347–354.

Lemaire, G. A., & Meisch, R. A. (1984). Pentobarbital self-administration in rhesus monkeys: Drug concentration and fixed-ratio size interactions. *Journal of the Experimental Analysis of Behavior,* **42,** 37–49.

Lemaire, G. A., & Meisch, R. A. (1985). Oral drug self-administration in rhesus monkeys: Interactions between drug amount and fixed-ratio size. *Journal of the Experimental Analysis of Behavior,* **44,** 377–389.

Logue, A. W., & Chavarro, A. (1987). Effect on choice of absolute and relative values of reinforcer delay, amount, and frequency. *Journal of Experimental Psychology: Animal Behavior Processes,* **13,** 280–291.

Mazur, J. E. (1988). Choice between small certain and large uncertain reinforcers. *Animal Learning & Behavior,* **16,** 199–205.

Meisch, R. A., Henningfield, J. E., & Thompson, T. (1975). Establishment of ethanol as a reinforcer for rhesus monkeys via the oral route: Initial results. In M. M. Gross (Ed.), *Advances in experimental medicine and biology: Vol. 59. Alcohol intoxication and withdrawal: Experimental studies II* (pp. 323–342). New York: Plenum Press.

Meisch, R. A., Kliner, D. J., & Henningfield, J. E. (1981). Pentobarbital drinking by rhesus monkeys: Establishment and maintenance of pentobarbital-reinforced behavior. *Journal of Pharmacology and Experimental Therapeutics,* **217,** 114–120.

Meisch, R. A., & Lemaire, G. A. (1988). Oral self-administration of pentobarbital by rhesus monkeys: Relative reinforcing effects under concurrent fixed-ratio schedules. *Journal of the Experimental Analysis of Behavior,* **50,** 75–86.

Miller, J. T., Saunders, S. S., & Bourland, G. (1980). The role of stimulus disparity in concurrently available reinforcement schedules. *Animal Learning & Behavior,* **8,** 635–641.

Snyderman, M. (1983). Delay and amount of reward in a concurrent chain. *Journal of the Experimental Analysis of Behavior,* **39,** 437–447.

Received December 27, 1988
Final acceptance May 16, 1989