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# COCAINE AND FOOD AS REINFORCERS: EFFECTS OF REINFORCER MAGNITUDE AND RESPONSE REQUIREMENT UNDER SECOND-ORDER FIXED-RATIO AND PROGRESSIVE-RATIO SCHEDULES

D. J. SPEAR AND J. L. KATZ

JOHNS HOPKINS UNIVERSITY SCHOOL OF MEDICINE AND
NIDA ADDICTION RESEARCH CENTER

Reinforcer magnitude and fixed-ratio requirement were varied under two second-order schedules. Under one, the first sequence of a fixed number of responses completed after the lapse of a 10-min fixed interval produced reinforcement. Under the second, a second-order progressive-ratio schedule, the fixed number of responses increased after each reinforcement. Either cocaine (0 to 300 μg/kg/inj) or food (0 to 5,700 mg/delivery) reinforcers were delivered. Under some conditions, a 2-s illumination of stimulus lights occurred on completion of each ratio sequence. Under the second-order schedule, as cocaine dose or amount of food increased, rates of responding increased; at the highest values, rates of responding decreased. Increases in the ratio requirement from 10 to 170 responses minimally decreased overall response rates. Under the second-order progressive-ratio schedule, increases in dose of cocaine or amount of food increased rates of responding; at the highest amounts of food, rates of responding decreased but response rates at the highest dose of cocaine remained relatively high. The highest ratio requirement that was completed (breaking point) depended on the dose of cocaine but was less dependent on the amount of food. Removing brief-stimulus presentations had a greater effect on completion of ratio requirements with cocaine compared to food.

*Key words:* cocaine, second-order schedules, progressive-ratio schedules, self-administration, reinforcing efficacy, lever press, squirrel monkeys

Under second-order schedules, the reinforcer is presented according to a schedule in which completion of an extended sequence of behavior is intermittently reinforced (e.g., the first completion of a sequence of 10 responses [fixed-ratio 10 or FR 10] after the lapse of a 5-min fixed interval [FI 5]). This second-order schedule is designated FI 5 (FR: S), where S signifies that a stimulus change occurred after completion of each FR unit (Kelleher, 1966). These schedules have been used extensively for studying the reinforcing effects of drugs. Unlike less complex schedules, under second-order schedules behavior can be maintained with relatively few drug injections per session, reducing the behavioral disruption that can be obtained under schedules in which drug injections recur throughout experimental sessions (Goldberg, 1976; Kelleher, 1976). Thus, under second-order schedules behavior maintained by the drug can be more directly compared to behavior maintained by more conventional reinforcers in determining whether they are comparably affected by environmental variables (Goldberg & Kelleher, 1977; Katz & Goldberg, 1991). Two variables that have previously been shown to affect responding under second-order schedules are reinforcer magnitude and response contingency.

Goldberg, Kelleher, and Goldberg (1981) studied the effects of reinforcer magnitude under an FI 5-min (FR: S) second-order schedule. With both cocaine (0 to 400 μg/kg/inj) and food (0 to 4,000 mg/delivery), response rates first increased and then decreased as the magnitude of the reinforcer was increased. Most studies with multiple reinforcer deliveries per session (cf. Balster & Schuster, 1973; Goldberg, 1973; Goldberg & Kelleher, 1976; Goldberg et al., 1981; Katz, 1989; Kelleher & Goldberg, 1977; Spealman & Kelleher, 1979) have found response rate to be an inverted U-shaped function of both food and cocaine reinforcer magnitude, although there may be differences in the highest response rates maintained or the reinforcer magnitude at which this maximum occurs (see Young & Herling, 1986).

There have been few studies directly comparing response requirements under second-order schedules of cocaine injection or food presentation. In one study, acquisition response rates under second-order schedules were

Send correspondence and reprint requests to D. J. Spear, Department of Psychiatry and Behavioral Sciences, Johns Hopkins University School of Medicine, 720 Rutland Ave., Baltimore, Maryland 21205.

higher under parameter values FI 5 (FR 3: S) than under the values FI 5 (FR 10: S) (Goldberg & Kelleher, 1977). With repeated exposure, however, both schedules maintained high, consistent response rates. Goldberg (1973) studied responding under a second-order FI 5 (FR: S) schedule with ratio sizes of 10 or 30 with both cocaine (0 to 400 $\mu$g/kg/inj) and food (0 to 1,000 mg/kg/delivery) reinforcers. Under the FR 30 requirement, steady-state response rates were the same or slightly higher than response rates under the FR 10 requirement. The dose–effect curves were qualitatively similar across FR values for both reinforcers (i.e., an inverted U-shaped function). However, maximal rates of responding were higher under the FR 30 than under the FR 10 schedule value for responding maintained by food in all 3 subjects and for responding maintained by cocaine in 1 of 3 subjects. These studies suggest that FR requirement may have some effect on response rates under the second-order schedule, although this effect has not been consistent across subjects. To date, only fairly low response requirements have been investigated, and the extent of ratio size effects has not been fully investigated.

The current study is an attempt to compare changes in responding maintained by either food or cocaine as a function of both schedule requirement and reinforcer magnitude under second-order schedules. To this end, the effectiveness of a range of magnitudes of cocaine or food in maintaining response rates, along with effects of increasing response requirements under the second-order FI 10 (FR: S) schedule, were studied.

Under the second-order schedule, evaluating FR values requires presentation of a particular value for several sessions, obtaining stable response rates, and presenting a new FR value for several more sessions until responding becomes stable again. This must be done for each FR value and each dose studied. In the present study, we also examined a second-order progressive-ratio schedule that offered a more expeditious procedure for evaluating the effects of ratio value under second-order schedules because ratio size was incremented from one interval to the next within a session (see Hodos & Kalman, 1963).

Under progressive-ratio schedules, the highest ratio value that maintains responding, the breaking point, has been used as an index of reinforcer efficacy (Griffiths, Bradford, & Brady, 1979; Griffiths, Brady & Snell, 1978; Hodos & Kalman, 1963; Winger & Woods, 1985). Most studies show that breaking-point value is an inverted U-shaped function of reinforcer magnitude; the present study attempted to verify this relationship for the second-order progressive-ratio schedule and to compare breaking-point values for food and cocaine reinforcers.

Second-order schedules are useful in part because they can be used to assess the conditioned reinforcement effects of stimuli scheduled with the reinforcer (Kelleher, 1966; Schindler, Katz, & Goldberg, 1988). The current investigation also examined the effects of the brief stimulus at various FR values by omitting all but the brief stimulus that occurred during reinforcer delivery. This was done for both the second-order fixed-ratio and the second-order progressive-ratio schedules in an attempt to investigate any differences with respect to the FR value.

## METHOD

*Subjects.* Six squirrel monkeys (*Saimiri sciurea*), 3 naive and 3 with a history that included intravenous self-administration of psychomotor stimulants, participated in the study. The 3 naive subjects (S-486, S-786, and S-1286) were assigned to the food group, and the 3 experienced subjects (S-482, S-782, and S-984) constituted the cocaine group. When not in the experimental chamber, subjects were individually housed in stainless-steel cages with free access to water. Subjects studied with cocaine were maintained at their free-feeding weights (0.8 to 1.0 kg), whereas subjects studied with food were maintained at 85% to 90% of their free-feeding weights (0.7 to 0.9 kg). All subjects were given fresh fruit to supplement the diet at least once per week.

Each cocaine subject was surgically prepared with a polyvinyl chloride catheter implanted in either the jugular, femoral, or illiac vein. The distal end of the catheter was passed subcutaneously to exit through the back. Surgical procedures are detailed in Herd, Morse, Kelleher, and Jones (1969). These subjects were fitted with a nylon mesh jacket to protect the exposed portion of the catheter. Catheters were flushed with saline (0.9% NaCl) before and after each experimental session, and after each session they were sealed with stainless-steel obturators.

*Apparatus.* Two sound-attenuating isolation chambers (Model AC-3, Industrial Acoustics) housed the Plexiglas restraining chairs in which subjects were seated during experimental sessions. A response lever (121-05, BRS/LVE) was located on the right side of the front panel of the chair, facing the subject. Depression of the response lever with a force greater than 15 g resulted in an audible feedback click and was recorded as a response. Mounted behind the clear front panel at eye level were three pairs of 6-W bulbs (green, amber, and red) that could be illuminated to serve as stimuli. Also located on the front panel was a recessed receptacle for delivery of 190 mg dustless banana-flavored pellets (Bio-Serve). A motor-driven syringe pump for IV drug administration was located outside the experimental chamber and could be connected to the catheter by way of polyethylene tubing that was passed through a small hole in the side of the chamber. The syringe pump was held braked by a small DC voltage except when its 110-V AC motor was operated by the programming equipment. White noise was continuously present within the chamber to mask extraneous noises. Chambers were connected to electromechanical and SKED® programming and recording equipment located in a separate room.

*Procedure.* Experimental sessions were conducted Monday through Friday. Cocaine subjects required no training. For all other subjects, training consisted of first accommodating subjects to the restraint chair. Food pellets were then delivered independently of behavior, each accompanied by a 2-s illumination of amber lights. When the subject was consistently obtaining all pellets delivered, lever pressing was shaped by the method of successive approximations (Ferster & Skinner, 1957). The green stimulus lights were then illuminated at all times except during food delivery, and responding was maintained under an FR 1 schedule. The ratio requirement was gradually increased until responding was stable under an FR 10 schedule. A short timeout, during which the chamber was dark and lever presses had no scheduled consequences, was then introduced following each pellet delivery and was gradually increased to 1 min over successive sessions. The second-order schedule was introduced by initially setting the FI schedule at a few seconds and increasing the value over sessions to the final 10-min value.

*Second-order schedule.* During illumination of the green stimulus lights, completion of each FR sequence was followed by a brief 2-s illumination of the amber lights, during which the green stimulus lights were out. The first FR unit completed after the lapse of a 10-min fixed interval turned off the green lights, turned on the amber lights for 2 s, and was followed by either a cocaine injection or food pellets. Following delivery of the reinforcer, a 1-min timeout occurred, in which all lights were extinguished and responses had no scheduled consequence. Each session ended after six deliveries of the reinforcer or 30 min with no responses.

Magnitude of the reinforcer, effects of removing the brief stimulus, and size of the FR requirement were studied under the second-order schedule. With the FR requirement constant, drug doses of 10, 30, 100, or 300 $\mu$g/kg/inj and saline were examined. Magnitude of the food reinforcer was varied by delivering 0, 1, 3, 10, or 30 of the 190-mg pellets. All pellets that had been delivered but not eaten were made available in the home cage after the session. Each drug dose or amount of food was studied for at least 10 sessions and until stable response rates were produced. For the FR 10 value, reinforcer magnitudes were presented in a mixed sequence. With all subsequent FR values, the magnitude that had maintained the highest response rates under the preceding condition was presented first, with subsequent magnitudes presented in a mixed sequence. At each FR value, the magnitude that had maintained the highest overall response rates was studied again. Brief-stimulus effects were then examined by removing illumination of the amber lights after all FR completions, except the one that accompanied drug injection or food delivery. These conditions were in effect for at least five sessions before the brief stimulus was reinstated.

Following determinations of effects of all reinforcer magnitudes at each FR value, the FR requirement was increased. Several FR requirements (10, 30, 100, and 170) were studied, starting with the smallest and progressing to the next larger. Responding of each subject was studied under all values, except S-786 and S-1286. With each FR value, values of reinforcer magnitude were examined in a mixed sequence as described above.

*Second-order progressive-ratio schedule.* After completion of all of the above conditions, responding maintained by food in Subjects S-786 and S-486 and responding maintained by cocaine in Subjects S-482 and S-782 were studied under the second-order progressive-ratio schedule. As before, each FR completion resulted in a 2-s illumination of the amber lights, the FI value was 10 min, and the first FR sequence completed after the lapse of a 10-min FI produced reinforcement. Under the second-order progressive-ratio schedule, if the schedule requirements were fulfilled the FR value was incremented for the next interval. Six ratio values were possible per session: 10, 30, 100, 300, 1,000, and 3,000. If the ratio was not completed within 10 min after the lapse of the FI, the timeout was presented without drug injection or food presentation, and the requirement was reset to FR 10 for the next interval. Sessions lasted until the opportunity to obtain six reinforcers occurred and always began with FR 10. The same magnitudes of cocaine dose or food amount were presented as under the second-order FR schedule; reinforcer magnitudes were presented in a mixed sequence. Each was initially presented for at least 10 sessions, or until responding became stable. At each dose of cocaine or amount of food, the brief stimulus was removed for at least five sessions. On occasion, the brief stimulus was reinstated with the same cocaine dose or number of pellets to redetermine rates prior to presentation of the next reinforcer magnitude.

*Data analysis.* Overall response rates were obtained by calculating responses per second during the time when lever presses could be reinforced (i.e., during the time when the green stimulus lights were illuminated). Response rates for each interval of the last three sessions at each reinforcer magnitude under the second-order FR schedule were averaged. Response rates under the second-order progressive-ratio schedule were averaged for each reinforcer magnitude, irrespective of FR value. Mean overall response rates under the second-order progressive-ratio schedule, irrespective of FR value, are also presented. Breaking point, defined as the highest ratio value under which responding occurred without completing the ratio requirement within the alloted time, was also determined. Each session yielded a single breaking point, and these values were averaged over the last three sessions for each reinforcer magnitude determination. A specific reinforcer magnitude was occasionally presented more than once under a particular FR value; data from all determinations were averaged.

*Drug and dosage.* Cocaine hydrochloride (provided by NIDA) was dissolved and diluted with a 0.9% saline solution. Dose per injection is expressed as microgram of the salt form of the drug per kilogram body weight of the subject.

## RESULTS

*Second-order schedule.* Figure 1 shows mean response rates for individual subjects under the second-order schedule for each FR value studied. Response rates increased as reinforcer magnitude (either cocaine dose or number of pellets) increased. At the highest reinforcer magnitudes, however, response rates increased less or decreased. This inverted U-shaped curve was observed for all subjects at most FR values. For S-782 with cocaine deliveries, the descending limb of the function was observed only at the FR 100 value. At lower FR values for this subject, the dose–effect curve continued to increase with dose, and at FR 170 only the highest cocaine dose maintained responding. (Responding could not be reliably maintained with lower cocaine doses at the higher ratio values for S-782.) The descending limb of the function was not obtained at FR 30 for either S-482 (cocaine) or S-1286 (food), although it was obtained for these 2 subjects at both higher and lower FR values. In general, higher response rates were maintained by food compared to cocaine.

Compared to reinforcer magnitude, FR value had a minimal effect on responding. In general, overall response rates were similar across FR values, with rate decreases seen consistently only at the higher FR values for S-782 (cocaine) and less so for S-786 (food). For S-1286 (food), mean overall response rates under the FR 10 were uncharacteristically low compared to FR 30 and FR 100 rates.

Saline maintained the lowest response rates under most conditions. For food-maintained responding, omission of all pellets generally maintained low response rates, although these were not always the lowest rates. The rein-

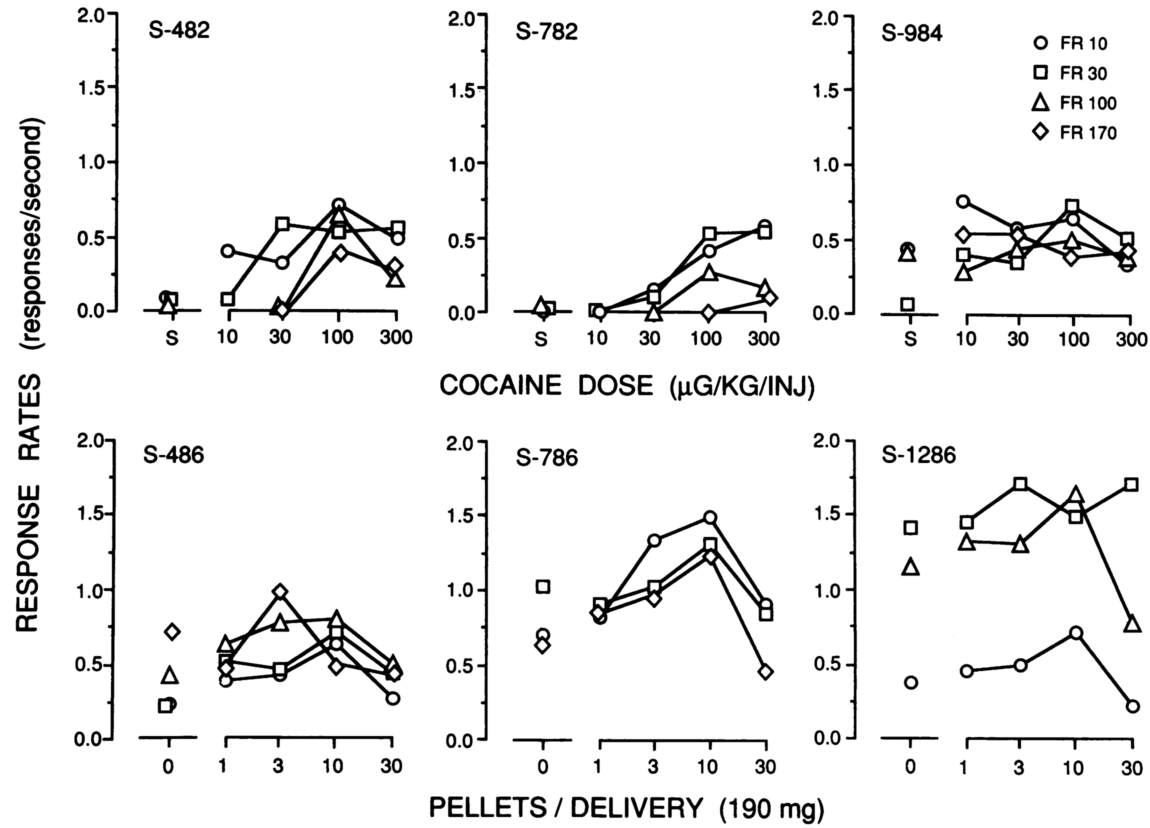


Fig. 1. Mean overall responses per second from the last three sessions for each subject under the second-order schedule. Averages are from the last three sessions at each FR value and reinforcer magnitude. Upper panels: cocaine-maintained responding; bottom panels: food-maintained responding. Unconnected symbols at S in the upper row denote saline sessions, and 0 in the bottom row denotes no pellets delivered. Some symbols have been offset to the left or right for clarity.

forcer magnitude that maintained maximal response rates for a particular subject was, ordinarily, the same across FR values. With a few exceptions, the highest rates of responding occurred with 100 μg/kg/inj cocaine or 10 pellets/delivery food. Although for each subject there were some irregularities, there was no consistency with respect to reinforcer type or FR value.

Figure 2 shows response rates maintained with and without the brief stimulus at selected FR values. Removing the brief stimulus decreased response rates under the lower FR values; however, the effects of removing the brief stimulus were inconsistent at the higher FR values.

Figure 3 shows representative performances of S-482 maintained by cocaine under the second-order schedule at FR 30 and FR 100 values. With 100 μg/kg/inj cocaine, there was a pause at the beginning of each interval, followed by high, consistent response rates. There were no reliable differences between FR 30 and FR 100 performances, although there was a slight trend for the pause at the beginning of each interval to increase with the ratio value. When the brief stimulus was omitted, pause duration at the beginning of each interval increased and pauses, once responding was initiated, were not uncommon. Saline maintained lower response rates, with long pauses at the beginning of each interval, and with frequent disruptions in rate of responding.

Figure 4 shows representative performances of S-486 maintained by food presentation. Response patterns were similar to those maintained by cocaine; however, there was a more gradual increase in rates across the interval. With the increase from FR 30 to FR 100, pauses at the beginning of each interval in-

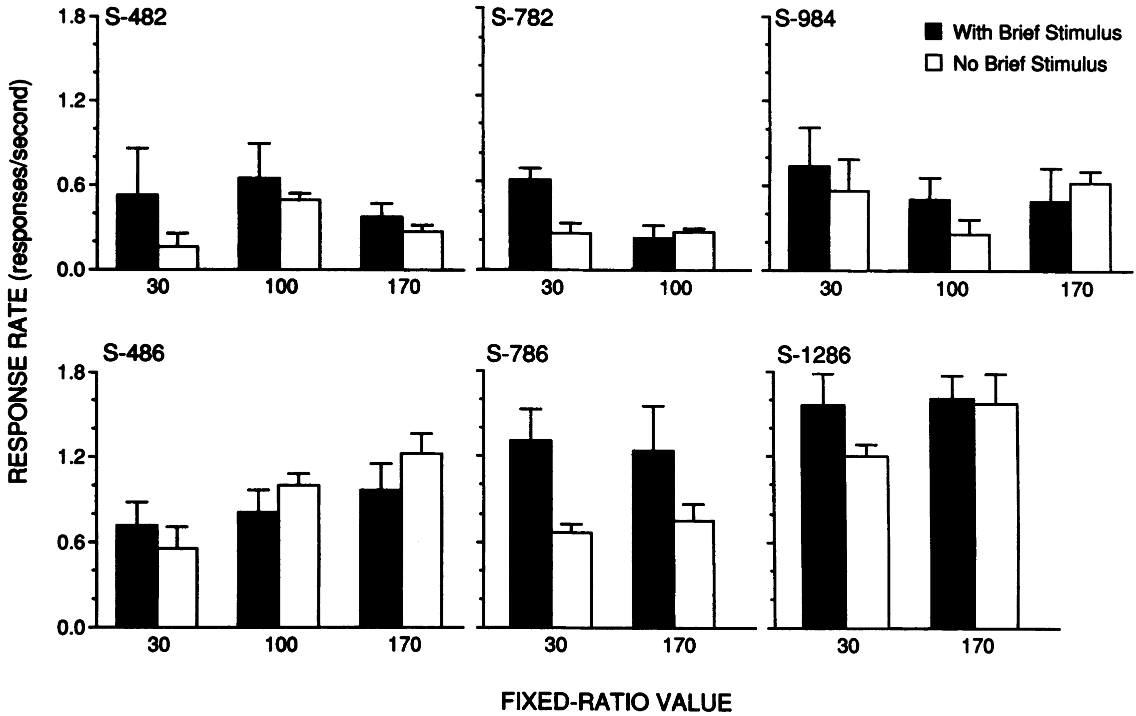


Fig. 2. Effects of brief stimulus omission on maximal rates of responding maintained by cocaine injection (top row) or food presentation (bottom row). Maximal effective magnitudes were for S-482: 100 μg/kg/inj cocaine under FR 30 and 100, and 300 μg/kg/inj under FR 170; S-782: 300 μg/kg/inj cocaine under FR 30 and 100; S-984: 100 μg/kg/inj under cocaine FR 30, 100, and 170; S-486: 10 pellets under FR 30 and 100, and 3 pellets under FR 170; S-786: 10 pellets under FR 30 and 170; and S-1286: 10 pellets under FR 30 and 170. Solid bars are the means of the last three sessions under conditions in which the brief stimulus was presented after each FR completion; open bars are the means of the last three sessions under conditions in which the brief stimulus was omitted. Brackets indicate +1 *SD*.

creased to about the same extent as those observed with cocaine-maintained responding. Removal of the brief stimulus increased pause duration at the beginning of the interval and decreased response rates, although these effects were not as pronounced as those observed with cocaine-maintained responding and were not obtained at the higher FR value. Omission of pellets at the time of reinforcer delivery disrupted the steady response rates, although response rates still tended to increase as the interval progressed.

*Second-order progressive-ratio schedules.* Representative performances of S-482 (cocaine) and S-486 (food) under the second-order progressive-ratio schedule are shown in Figure 5. A response pattern similar to that under the second-order fixed-ratio schedule was observed, with a pause at the beginning of each interval, followed by a high, steady response rate. There was little disruption in response patterns with increases in FR value until, at the higher FR values, cocaine-maintained responding became erratic and often ceased altogether. On those occasions when responding ceased, it often resumed towards the end of the session after the FR was reset to 10 responses (Figure 5). Omission of the brief stimulus decreased response rates and increased pause times at the beginning of and during each interval. Responding occasionally ceased at FR values that maintained responding with brief-stimulus presentations. Substitution of saline for drug or omitting the delivery of pellets greatly reduced responding and disrupted response patterns.

Average response rates under the second-order progressive-ratio schedule for all magnitudes are shown in Figure 6. An inverted U-shaped magnitude-effect curve was ob-

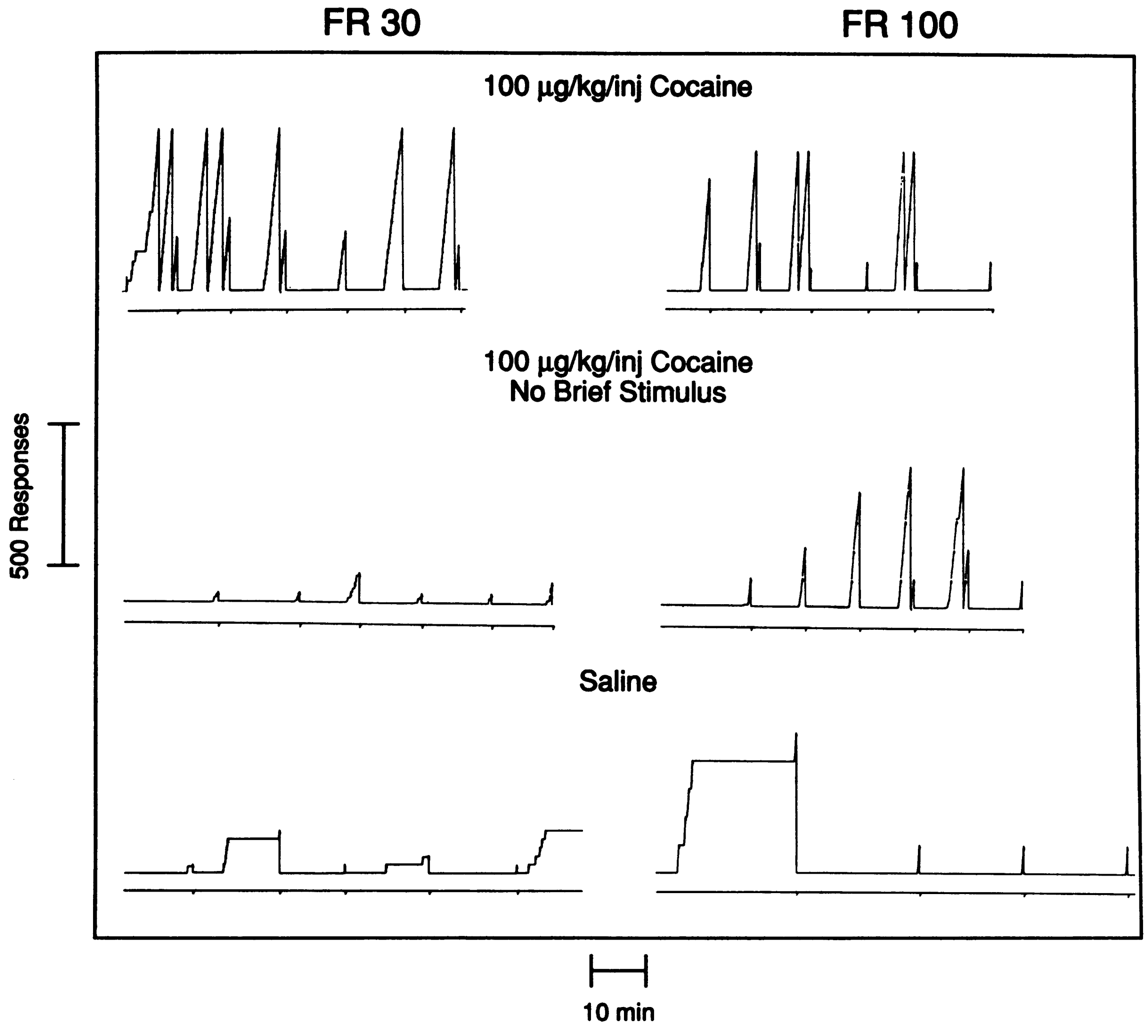


Fig. 3. Representative performances of S-482 under the second-order schedule maintained by 100 $\mu$g/kg/inj cocaine, 100 $\mu$g/kg/inj cocaine with the brief stimulus omitted, and saline. Records on the left are from sessions at FR 30; those on the right are from sessions at FR 100. The upper response pen incremented with each lever press, was deflected with each FR completion, and was reset at the end of each interval. Deflections of the bottom pen indicate the end of the interval. The recorder did not operate during reinforcer delivery or the timeout period.

tained for food-maintained responding, whereas cocaine-maintained responding tended to increase monotonically with dose. Absolute response rates were higher for food- than for cocaine-maintained responding. Saline maintained the lowest response rates, and the omission of food produced low, but not always the lowest, response rates. Omission of the brief stimulus consistently decreased mean response rates for both cocaine and food reinforcers.

Response rates with the dose of cocaine or amount of food that maintained maximal rates with and without brief-stimulus presentations are shown in Figure 7. Maximal response rates were maintained at 100 or 300 $\mu$g/kg/inj for S-482 or S-782, respectively. These doses generally maintained maximal response rates at each FR value. With food-maintained responding, the reinforcer magnitude that maintained the highest rate of responding was generally constant, at 10 pellets/delivery for S-786. For S-486, the amount of food that maintained highest response rates was either 3 or 10 pellets/delivery. When the brief-stimulus presen-

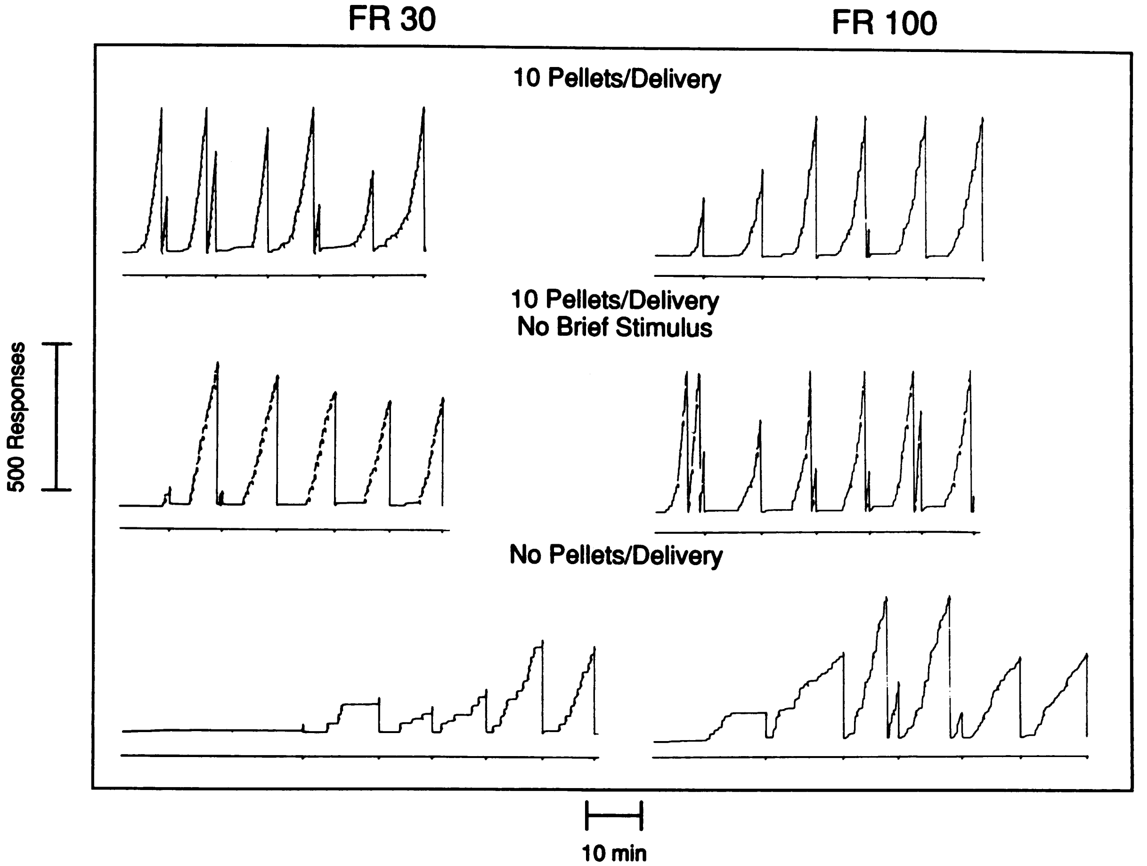


Fig. 4. Representative performances of S-486 under the second-order fixed-ratio schedule maintained by 10 pellets, 10 pellets with the brief stimulus omitted, and no pellets. Performances on the left are from sessions at FR 30; those on the right are from sessions at FR 100. Recording was as described for Figure 3.

tations were omitted, mean response rates generally decreased. These lower rates were observed for both subjects in the cocaine group and, with few exceptions, for both subjects in the food group.

The mean breaking point, the highest FR value at which responding was maintained, is shown in Figure 8. For cocaine-maintained responding with the brief stimulus, breaking point increased with increases in reinforcer magnitude, reaching asymptotic values between 100 and 300 μg/kg/inj. Food reinforcement maintained breaking points higher than those maintained by cocaine under the second-order progressive-ratio schedules with brief stimuli. Breaking point was generally unrelated to the amount of food, except for S-486 at the 10 pellets/delivery value (at which breaking points slightly increased) and the 30 pellets/delivery value (at which breaking points decreased). Breaking points for food-maintained responding were consistently at or near the highest possible ratio value. Omission of the brief stimulus decreased breaking point for cocaine-maintained responding, but there was little change in breaking-point values with brief-stimulus omission for food-maintained responding.

## DISCUSSION

The present study investigated the effects of reinforcer magnitude and response requirement on response rates under second-order fixed- and progressive-ratio schedules. The effects of reinforcer magnitude on responding under second-order fixed-ratio schedules were consistent with those previously reported (cf. Goldberg, 1973, 1976; Spealman & Kelleher, 1979); increasing cocaine dose or amount of

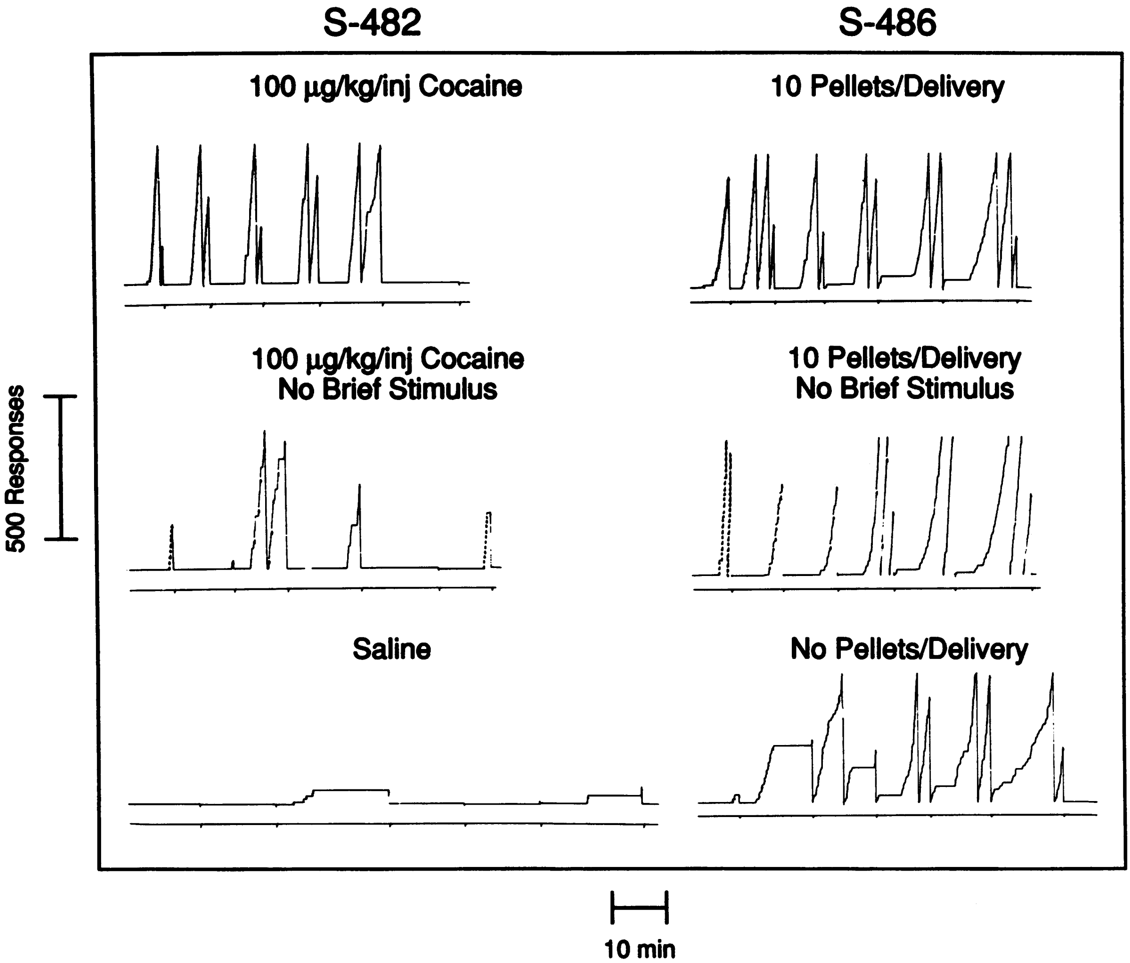


Fig. 5. Representative performances of S-482 (left column) under the second-order progressive-ratio schedule maintained by 100 $\mu$g/kg/inj cocaine, 100 $\mu$g/kg/inj cocaine with the brief stimulus omitted, and saline. Performances for S-486 under the same schedule but maintained by 10 pellets, 10 pellets with the brief stimulus omitted, and no pellets are shown on the right. Recording was as described in Figure 3.

food increased response rates with further increases in magnitude generally decreasing response rates. Increasing reinforcer magnitude under the second-order progressive-ratio schedule produced increasing response rates, with decreases in rates obtained when large amounts of food were presented but not when high doses of cocaine were presented. Within-session patterns of responding were characterized by a period of little or no responding, followed by a gradual increase in responding that was maintained until reinforcer delivery. When the brief stimulus was presented after completion of each ratio sequence, it was often followed by a short pause and a transition to an increased response rate. Removal of the reinforcer produced the lowest response rates with a disruption in the typical pattern. On occasion, however, removal of pellets did not appreciably decrease response rates.

Under both the second-order fixed-ratio and progressive-ratio schedules, mean overall response rates were strikingly similar across low to intermediate ratio requirements with little or no change in the reinforcer magnitude that maintained maximal response rates. The most prominent and consistent ratio-value effect on overall response rates was the inability of low doses of cocaine to maintain responding under the schedule with the highest ratio values. Under the second-order fixed-ratio schedule, low doses of cocaine did not maintain responding

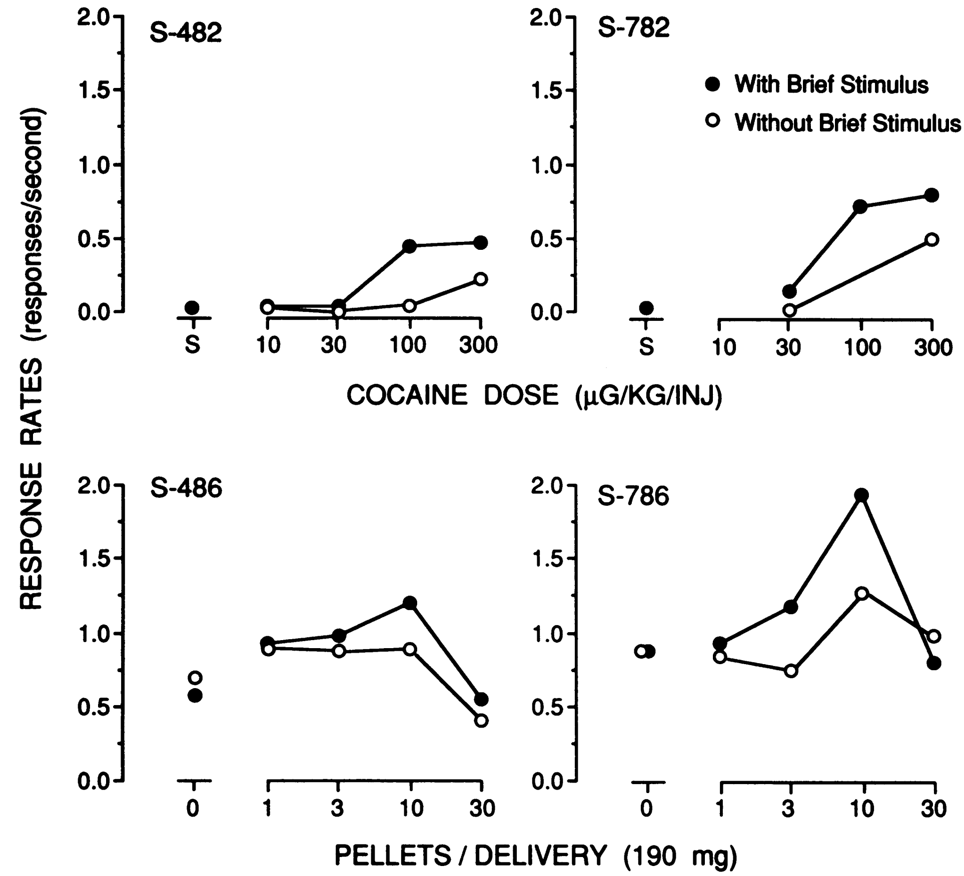


Fig. 6. Mean overall responses per second from the last three sessions for each subject under the second-order progressive-ratio schedule. Upper panels: cocaine-maintained responding; bottom panels: food-maintained responding. Filled symbols: sessions when the brief stimulus was presented after every FR completion; open symbols: sessions when the brief stimulus was omitted. Unconnected symbols at S in the upper row denote saline sessions, and 0 in the bottom row denotes no pellets delivered. Each symbol indicates response rates averaged across FR values. Thus, each symbol is the mean of all rates during the last three sessions for each magnitude. Some symbols have been offset to the left or right for clarity.

at values above FR 30. Along similar lines, Marquis, Webb, and Moreton (1989) found that response rates of rats self-administering phencyclidine were more disrupted by increases in the FR value at the lowest doses studied. Responding was maintained under the second-order progressive-ratio schedule under successively increasing ratio values at doses that did not maintain responding under the second-order fixed-ratio schedule. This maintenance of responding at ratio values that were successively approximated indicates that the recent history of the subject in part determines the performances maintained. A further implication is that breaking point on progressive-ratio schedules may depend on the sequence of ratio values that comprise the progression (see below).

The lack of a large effect on response rates with changes in FR value at the higher doses contrasts with several previous studies. For example, Pickens and Thompson (1968) found significant increases in response rates when the value of an FR schedule was increased from 5 to 80 responses with rats self-administering cocaine. They also found that as cocaine dose was increased, the highest FR value that maintained responding increased, in accordance with the present findings. Goldberg (1973) found that for some subjects under a second-order FI 5 (FR: S) schedule of IV cocaine injection, higher doses of cocaine were required to main-

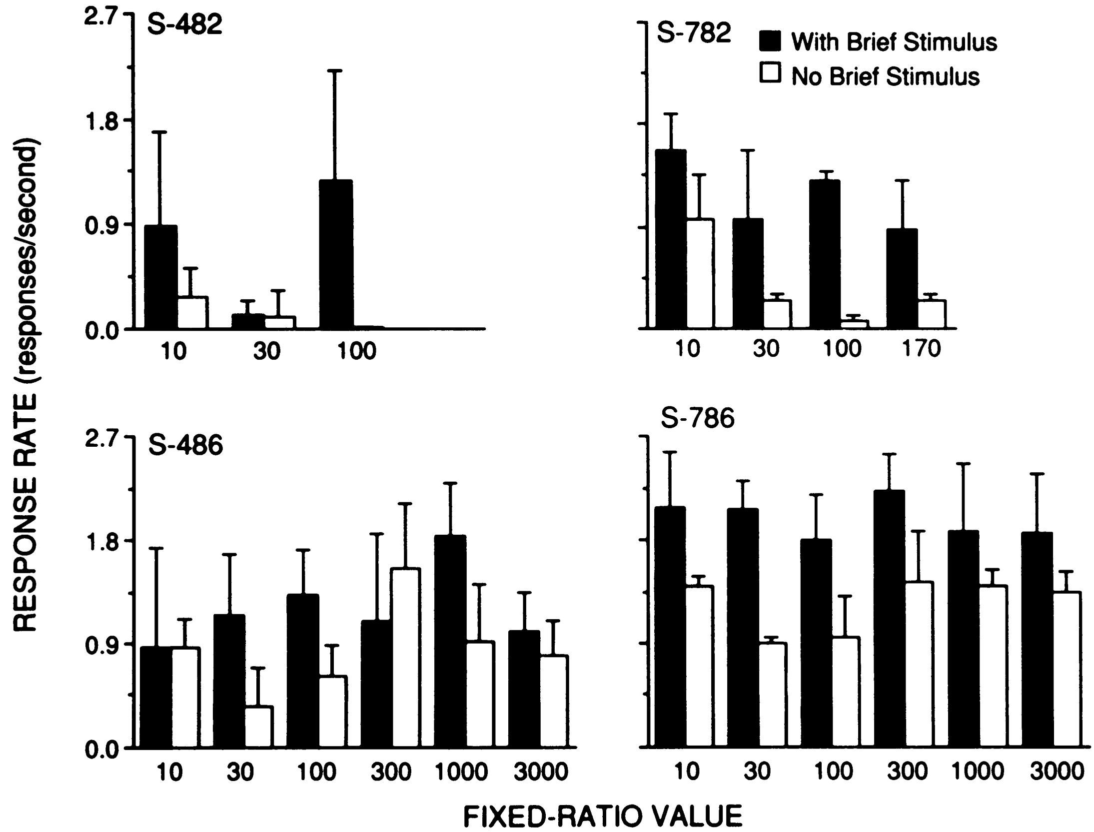


Fig. 7. Effects of brief-stimulus omission on maximal rates of responding maintained by cocaine injections (top row) and food presentations (bottom row). Maximal effective magnitudes were, for S-482: 300 μg/kg/inj under FR 10, and 100 μg/kg/inj cocaine under FR 30, 100, and 300; S-782: 300 μg/kg/inj cocaine under FR 30, 100 μg/kg/inj under FR 30 and 300, and 30 μg/kg/inj cocaine under FR 100; S-486: 10 pellets under FR 10, 300, and 1,000, 1 pellet under FR 30 and 3,000, and 3 pellets under FR 100; S-786: 10 pellets under FR 10, 100, 300, and 3,000, 3 pellets under FR 30, and 1 pellet under FR 1,000. Solid bars are the means of the last three sessions under conditions when the brief stimulus was presented after each FR completion; open bars are the means of the last three sessions under conditions when the brief stimulus was omitted. Brackets indicate +1 *SD*.

tain maximal responding at FR 30 compared to FR 10.

It is possible that differences in effects of FR value in the present and previous studies are due to the longer time between injections (at least 11 min in the current study compared to 6 min in the Goldberg, 1973, study and even shorter times in the Pickens and Thompson, 1968, study) or the lower range of FR values used in both of the previous studies. When response rates have been shown to vary with FR size, the schedule has usually been designed so that the total number of injections was directly dependent on response rate, where a transient decrease in response rate would decrease rate of reinforcement, which could further decrease response rates (cf. Pickens & Thompson). Under the present schedules this was not the case because the FI contingency limited the relation between rate of responding and rate of reinforcement (Ferster & Skinner, 1957). Changes in response rates that might have been produced by increasing the FR requirement could have little effect on the frequency of reinforcement.

The comparison between food- and cocaine-maintained responding in the present study should be made cautiously because no subject was studied with both reinforcers. However, because the functions relating response rate and reinforcer magnitude were qualitatively similar for food and cocaine reinforcers, sufficient ranges of reinforcer magnitude were studied to establish approximate correspon-

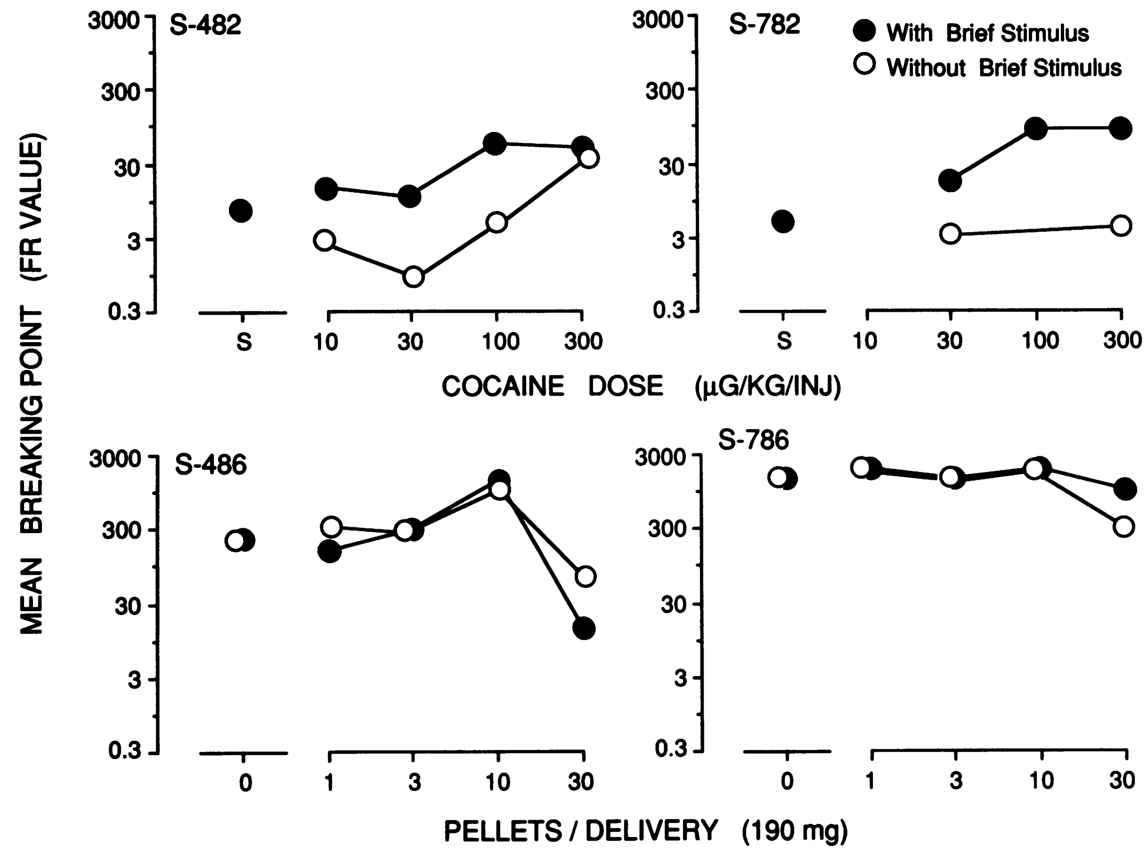


Fig. 8. Mean breaking points from the last three sessions for each subject under the second-order progressive-ratio schedule. Top panels: cocaine-maintained responding; bottom panels: food-maintained responding. Filled circles: brief stimulus was presented after each FR completion; open circles: brief stimulus was omitted. Unconnected symbols at S in the top panels denote saline sessions, and 0 in the bottom panels denotes no pellets were delivered.

dence. Under both schedules, food maintained higher overall rates of responding than did cocaine, with surprisingly little overlap in overall response rates across reinforcers. Thus, food appears to be more effective than cocaine as a reinforcer under the current conditions. Because high doses of cocaine can sometimes produce a decrease in response rates (Barrett & Katz, 1981; Katz, 1989), the effects of cumulative doses are often used as an explanation for low rates of cocaine-maintained responding; this explanation seems plausible under the present conditions. However, that responding was often reinitiated at lower ratio values after ceasing at the higher values suggests that the cessation was due to ratio size rather than to the effects of cocaine. Further, it was the lower cocaine doses that failed to maintain responding under the higher FR values, a result incompatible with the expected rate-decreasing effects of high cumulative cocaine doses but consistent with cocaine being relatively less effective than a food reinforcer.

Previous comparisons of cocaine- and food-maintained responding have focused on functional similarities emphasizing similar reinforcing effects of food and cocaine. Several studies have shown the ability of cocaine to maintain behavior in a manner analogous to food, but differences in food- and cocaine-maintained behavior have emerged. For instance, in addition to the previously mentioned differences in food and cocaine associated brief-stimulus effects (Goldberg et al., 1981), Katz (1980) found that response rates decreased at the highest doses of cocaine but not at the largest amounts of food (even when only one injection occurred per session, precluding rate-decreasing effects). Katz and Goldberg (1991) reviewed various schedule arrangements and concluded that overall rates of food-maintained responding have been shown to be higher, lower, and the same as rates maintained by cocaine. The reasons for these inconsistencies are as yet undetermined.

Because response rates can be influenced by drug effects other than reinforcing effects, alternative measures of reinforcer effectiveness have been examined. Breaking point determined under the progressive-ratio schedule is one measure that is less directly influenced by rate-altering drug effects. Comparing breaking points determined by different reinforcers under progressive-ratio schedules may provide indices of reinforcer efficacy (Griffiths et al., 1978; Griffiths, Findley, Brady, Dolan-Gutcher, & Robinson, 1975) and perhaps even quantification of their effectiveness (see Katz, 1990, for a discussion). When this comparison is applied to the current progressive-ratio data, it appears that food was relatively more effective as a reinforcer than cocaine, given the higher breaking points. Omission of the brief stimulus reduced the breaking point for responding maintained by cocaine injections but had little effect on the breaking point for responding maintained by food delivery. The differential effects of brief-stimulus removal suggest that cocaine-maintained response rates were, to a greater extent than food-maintained rates, dependent on presentation of this conditioned reinforcer. Whether the ability of a paired stimulus to maintain responding is dependent on the type of reinforcer cannot be determined from the present data, but given that Goldberg et al. (1981) found removal of the brief stimulus did not decrease food-maintained response rates under an FI 5 (FR) schedule, further study would be interesting and, perhaps, important.

The progressive-ratio schedule used in the present study is procedurally different from those used previously because this schedule was incorporated into a second-order schedule. The current schedule also differs from many of the previous progressive-ratio procedures in that the ratio increment occurred following each drug injection instead of across sessions. Given these seemingly major procedural differences, the similarities between the present study and previous studies are striking. Breaking points increased with increases in cocaine dose, approaching an asymptotic value at about 100 to 300 $\mu$g/kg/inj, similar to that found with rhesus monkeys (Winger & Woods, 1985), baboons (Griffiths et al., 1975, 1978), and rats (Roberts, Loh, & Vickers, 1989). In the primate studies, breaking point increased with cocaine dose up to about 300 $\mu$g/kg/inj, with further increases producing a decrease in breaking points.

There are at least two major advantages of the current modifications over the more typical progressive-ratio schedule. First, under the current conditions, stable breaking points could be determined in as little as 10 days per dose; this method offers expediency in data collection over both many of the previous progressive-ratio procedures and the second-order procedure of the current study. It is possible that breaking points and stable response rates could be determined with even fewer sessions by lengthening the session and presenting more intervals. Second, there are the benefits of using the second-order element of the current schedule in maintaining a high rate of complex behavior with few injections per session. The schedule arrangement shows promise as a means to maintain response requirements even higher than previous second-order schedules.

To some extent, the current breaking-point analysis may not accurately indicate the effectiveness of food as a reinforcer. Responding often occurred under the FR 3,000 requirement (the last ratio in the session) but was seldom completed within the time constraint. Had the session or time requirement been extended, it is possible that higher ratio requirements could have been maintained. This schedule constraint can be seen in Figure 8, as relative invariance of breaking points with amount of food and lack of a decrease in breaking points with brief-stimulus removal. Step size of the progressive-ratio progression has been shown to affect breaking points and the relation of breaking point to antecedent variables such as food deprivation (Hodos & Kalman, 1963). The logarithmic progression used may have affected breaking points. The progression of FR sizes under the current second-order schedule suggests that smaller progressions according to a different scale might produce quite different breaking-point values.

Comparisons among drugs in preclinical studies assessing abuse liability suggest that there may be valid and reliable methods for quantifying the effectiveness of different reinforcers. Both response rate and breaking-point measures of the current study suggest that the relative reinforcing efficacy of food is greater than that of cocaine. This ordering of reinforcers differs from that of Aigner and Balster (1978). When rhesus monkeys received cocaine or food under a choice procedure, cocaine-maintained responding predominated to the extent that subjects rarely received food and the experimenters had to intervene.

Previous studies have suggested that different techniques for assessing the relative effectiveness of reinforcers can produce different results. For example, Brito (1985) examined the reinforcing effects of water in Brattleboro and normal Long-Evans rats. Brattleboro rats, being homozygous for diabetes insipidus, have daily water intakes that are much higher than normal rats. Progressive-ratio performances maintained by water presentation and the suppression of water intake by quinine adulteration were examined. Although more quinine was necessary to suppress water consumption in the diabetic compared to the normal rats, their breaking points under the progressive-ratio schedule were lower. Results such as these caution against broad conclusions based on isolated comparisons of two reinforcers, and indicate that a comprehensive assessment of reinforcing efficacy will require extensive systematic studies yielding significant correspondence.

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