**DRUG EFFECTS ON FIXED-INTERVAL RESPONDING
WITH PAUSE REQUIREMENTS FOR
FOOD PRESENTATION¹**

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In pigeons performing under a multiple schedule of food presentation, low key-pecking rates (0.18 to 0.29 responses per second) were maintained during 3-min fixed-interval components by requiring a 4-, 5-, or 6-sec pause preceding the food-delivery response (tandem DRL), while higher rates (0.70 to 1.37 responses per second) were maintained in alternate fixed-interval components by requiring a pause of no more than 40 msec preceding the food-delivery response (tandem DRH). Thus, reinforcement density was equal but overall response rates markedly different in the two schedule components. Pentobarbital (3, 10 mg/kg) had effects on overall rates of responding consistent with a rate-dependency interpretation (low rates were increased while higher rates were decreased), but *d*-amphetamine (0.03 to 3 mg/kg) either failed to increase low overall rates in the tandem DRL components or increased them only slightly. Effects of both drugs on local responding within the fixed-intervals were always related in an orderly way to control response rate, but the extent of rate increases produced by *d*-amphetamine was modified in some birds by pause requirements such that the drug increased comparable rates less when these occurred in the tandem DRL component than when they occurred in the tandem DRH components. Control rate is an important determinant of drug effects, independent of reinforcement density maintaining rates, and independent of environmental influences, such as response-spacing requirements for food presentation, that can modify the extent of some drug-produced rate changes.

Key words: pacing requirements, tandem FI DRL, tandem FI DRH, rate dependence, pentobarbital, *d*-amphetamine, pigeons

The effects of drugs on schedule-controlled behavior are generally related in an orderly way to on-going control rates of responding. At appropriate doses, drugs representing diverse pharmacological classes such as amphetamine (Dews, 1958; Smith, 1964), chlorpromazine (Dews, 1965), diazepam (Wuttke and Kelleher, 1970), and amobarbital (McKearney, 1970) increase responding when control rates are low and decrease responding when control rates are high. These relationships, at least for *d*-amphetamine, are relatively independent of specific schedules and schedule parameters that maintain responding (McMillan, 1969; Leander and McMillan, 1974). In a study by McMillan (1969), for example, *d*-amphetamine increased low rates of responding and decreased high rates in pigeons, irre-

spective of whether these rates were generated under fixed-interval or fixed-ratio schedules of food delivery.

Interpretation of drug effects on rates maintained under different schedules of reinforcement is complicated somewhat, however, by the fact that high rates of responding are generally correlated with high reinforcement densities and low rates with low reinforcement densities (Morse, 1966). Thus, reinforcement density, rather than rate *per se*, could be determining drug effects. MacPhail and Gollub (1975) showed that effects of *d*-amphetamine and scopolamine in both rats and pigeons were rate-dependent even when reinforcement density was held constant. These investigators utilized pacing requirements preceding the food-delivery response during three components of a multiple variable-interval schedule (tandem VI DRL schedule) to generate three different response rates maintained by equal densities of reinforcement delivery. In the present experiments, high and low rates of responding were maintained by equivalent

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densities of reinforcement available under a fixed-interval schedule. Response rate was manipulated within the fixed-interval components by requiring either a long (4, 5, 6 sec, or more) or a short (40 msec or less) pause before the food-delivery response.

Although control response rate is an important determinant of drug effects on behavior, it may not be the only determinant. It has been demonstrated that certain environmental variables can modify the effects of drugs on behavior. For example, the rate-increasing effect of amobarbital is lessened (McKearney, 1970), and that of *d*-amphetamine virtually eliminated (Thompson and Corr, 1974), when responding is under relatively strong control by environmental discriminative stimuli. The present study also sought to determine whether pause requirements preceding the food-delivery response would modify drug effects during the fixed-interval. This was accomplished by comparing drug effects on equivalent local response rates occurring within the two fixed-interval schedule components.

METHOD

Subjects

Five male White Carneaux pigeons were food deprived and maintained at 80% of free-feeding body weights. All had histories of responding under schedules of food delivery and most had received drugs in previous experiments.

Apparatus

Experimental chambers measured 33 by 28 by 34 cm high. A round, translucent Plexiglas response key (2.5 cm in diameter), which could be illuminated from behind with pairs of 7-W colored lights, was located in the center of the front panel, 24 cm from the floor. A peck on this key of 15 g (0.15 N) force or greater broke an electrical contact, was recorded as a response, and produced the audible click of a relay mounted in the chamber. Four-second access to grain could be given through a 4.5-by 5-cm opening located below the response key. A low level of white masking noise was present at all times in the chamber. Programming and data recording were accomplished with electromagnetic relay equipment located in an adjoining room.

Procedure

Two components of a multiple schedule, one signalled by a white keylight and the other by a red keylight, alternated during the session. In both components, 4-sec access to grain could be obtained for a response made after the end of a 3-min interval (timed from the end of the previous grain delivery), while responses during the interval were recorded but had no consequences. Initially, when the white keylight was on, grain was delivered for the first response following the end of the interval (fixed-interval 3-min schedule), and when the red keylight was on, grain was delivered following the end of the interval for the first response preceded by a pause of at least 4 sec in Birds 63 and 181, 5 sec in Birds 874 and 2987, and 6 sec in Bird 266 (tandem FI 3-min DRL *t*-sec schedule). The clock that set the minimum pause length started at the end of the interval, and responses made while the clock was running (*i.e.*, those that did not meet the DRL requirements) reset the clock. This component is referred to as the tandem DRL component. Key color switched after each grain delivery and sessions terminated after 20 component presentations.

After exposure to this multiple schedule for two to 10 days (median = six days), the fixed-interval component was eliminated and sessions consisted of 20 tandem DRL components alone for four to 14 days (median = 11 days). Then, the fixed-interval component correlated with a white keylight was re-instated, with the schedule modified such that grain was delivered following the end of the interval for the first response preceded by a pause of 40 msec or less (tandem FI 3-min DRH 40-msec schedule). This component is referred to as the tandem DRH component. From this point in the experiment, if either pause requirement was not met within 2 min after the 3-min interval had elapsed, the keylight color changed and access to grain could not be obtained until the end of the next 3-min interval (2-min limited-hold). Drug administration began after eight to 16 days' exposure to this terminal schedule.

Drugs. Sodium pentobarbital (3, 5.6, and 10 mg/kg) and *d*-amphetamine sulfate (0.03, 0.3, 1, and 3 mg/kg) were injected into the pectoral muscle (volume = 1 cc/kg) 10 min before the experimental session. *d*-Amphetamine was dis-

solved in saline and doses are as the base of the drug; pentobarbital was dissolved in distilled water and doses are as the salt. Drugs were usually given twice a week (Tuesday and Friday), providing that rates and patterns of control responding on the previous day fell within the range of previously observed values. Each bird received all indicated doses of both drugs, except Bird 874, which received 0.3, 0.56, and 1 mg/kg of *d*-amphetamine, and each dose was replicated two or three times in each bird.

Data analysis. The number of responses per second in each schedule component (including time spent meeting the pause requirements after the end of the fixed-interval) averaged over an entire session is referred to as the overall response rate. The number of responses occurring during successive tenths of the 3-min fixed-interval, averaged over the entire session, is referred to as local response rate. Local responding does not include responding that occurred after the end of the fixed interval. The average proportion of the 3-min interval that elapsed before the bird emitted one quarter of the total responses in the interval is a measure of response patterning that is independent of rate, and is referred to as the quarter-life value (Gollub, 1964; Herrnstein and Morse, 1957).

For the rate-dependency analysis, drug-rate/control-rate ratios (using control data from the previous nondrug day) were calculated for each tenth of the fixed interval and plotted (on log-log coordinates) as a function of control response rate in that tenth of the fixed-interval. Regression lines were fit separately to data points from the two schedule components by the method of least squares.

RESULTS

Control performance. When birds were initially exposed to the tandem DRL requirement, grain delivery was occasionally delayed up to 15 min, due to extended periods of responding at rates too high to meet the pause requirements of 4, 5, or 6 sec in individual birds, but rates decreased with additional exposure to the tandem DRL contingency. Addition of the tandem DRH 40-msec requirement during alternate components resulted in an immediate increase in response rates during these components in three birds with the

Fig. 1. Examples of control responding before drug administration for Birds 63 and 266. The response pen steps up with each key peck and resets at the end of food delivery or the end of the 2-min limited hold. The event pen deflects at the onset of reinforcement availability and resets at the end of food delivery or the end of the limited hold. Brackets under alternate components indicate intervals where a pause of 4 sec (Bird 63) or 6 sec (Bird 266) was required preceding the food-delivery response (tandem DRL components). The absence of brackets signifies the presence of the tandem DRH components.

lowest initial rates; response rates in the tandem DRL components for all birds were relatively unaffected by addition of the tandem DRH requirement. Response rates ranged from 0.29 to 0.35 responses per second in the tandem DRL components and from 0.53 to 0.92 in the tandem DRH components during the first five days of exposure to the final schedule. Response rates in the two components continued to diverge over time, and stable control rates differed markedly in the two schedule components at the time drug administration began.

As shown in the examples of control performance in Figure 1, temporal patterning of responses was generally similar in the two schedule components: a short pause after grain delivery was followed by a gradually increasing response rate until access to grain occurred again. Average quarter-life values were $0.55 (\pm 0.05 \text{ S.D.})$ and $0.45 (\pm 0.05 \text{ S.D.})$ in the tandem DRH and DRL components, respectively, during the five days before drug administration began. Quarter-life values increased in both components over the course of the experiment, and were $0.63 (\pm 0.03 \text{ S.D.})$ and $0.58 (\pm 0.07 \text{ S.D.})$ in the tandem DRH

Fig. 2. Dose-effects of *d*-amphetamine and pentobarbital on overall rates of responding in five individual birds. Drug-produced rate changes are shown separately for tandem DRL (bottom) and tandem DRH (top) components. Each point represents the average of at least a duplicate drug determination. Brackets at C are ± 1 standard deviation. Data for *d*-amphetamine 3 mg/kg are as follows: in the tandem DRH component; Bird 63, 0.52 response/second; Bird 181, 1.00 response/second; Bird 266, 0.17 response/second; Bird 2987, 0.53 response/second. In the tandem DRL component: Bird 63, 0.57 response/second; Bird 181, 0.33 response/second; Bird 266, 0.22 response/second; Bird 2987, 0.17 response/second. Data for *d*-amphetamine 0.56 mg/kg in Bird 874 are: 0.78 response/second in the tandem DRH component, 0.24 response/second in the tandem DRL component.

and DRL components, respectively, during control days preceding the last five drug administrations. Access to grain was obtained in both schedule components shortly after the end of the intervals, but average time spent with the tandem DRL components in effect was typically longer and more variable than time spent with the tandem DRH components in effect (see Figure 5).

Drug effects on overall rates of responding. Figure 2 shows response-rate changes produced by *d*-amphetamine and pentobarbital in the two schedule components for individual birds. High overall rates during the tandem DRH components were frequently unchanged by either drug, and when changes occurred, both rate increases and decreases were observed. Moderate doses of *d*-amphetamine (0.3 and 1

mg/kg) increased high rates in three of five birds (63, 181, and 266); pentobarbital at 3 and 5.6 mg/kg increased high rates in one bird (2987). The largest dose of pentobarbital (10 mg/kg) decreased high overall rates below control values in two birds (63 and 874), as did *d*-amphetamine 1 mg/kg (Birds 874 and 2987). A dose of 3 mg/kg *d*-amphetamine markedly decreased high rates in Birds 63, 266, and 2987, but left these rates unchanged in Bird 181. In the tandem DRL components, pentobarbital increased low overall rates in a dose-related manner, while *d*-amphetamine failed to increase these rates or produced only slight rate increases.

Drug effects on local rates of responding. Figures 3 and 4 show the effects of pentobarbital and *d*-amphetamine on local responding

Fig. 3. Rate-dependent effects of pentobarbital 3, 5.6, and 10 mg/kg on local responding in five individual birds. (Bird identification numbers are given on the right.) Drug-rate/control-rate ratios for each one-tenth segment of the fixed-interval are plotted (log scale) as a function of average control rate in that one-tenth segment on the day before drug (log scale). Each graph contains data from two or three replications of the dose indicated, and data points were excluded only if zero responses occurred in the segment on either drug day or the preceding control day. Horizontal lines within each graph represent a ratio of 1, or no drug-produced rate change. Points falling above the line represent drug-produced rate-increases, while points falling below this line represent drug-produced rate-decreases. Points toward the left-hand side of each graph represent relatively lower rates occurring in the early portion of the intervals; points falling toward the right-hand side of each graph represent relatively higher rates occurring in the later portion of the intervals. Least-squares regression lines have been fitted to data from the two components. Filled circles and solid lines are data from the tandem DRH components; unfilled circles and broken lines are data from the tandem DRL components.

within the intervals for all individual birds. Data are expressed as proportional drug-produced rate changes in successive one-tenth segments of the interval, plotted as a function

of control response rate for that one-tenth segment. Both drugs produced rate changes related in an orderly way to control responding. Low rates in both schedule components

Fig. 4. Rate-dependent effects of *d*-amphetamine on local responding in five individual birds. Data for 0.03, 0.3, and 1 mg/kg *d*-amphetamine are shown for four birds; data for 0.3 and 0.56 mg/kg are shown for Bird 874, since the 1 mg/kg dose eliminated responding in this bird on two of four occasions when the dose was given. All explanations of the graphs are as in Figure 3.

were increased and the magnitude of increase was inversely related to control response rate; relatively higher rates occurring late in the tandem DRH intervals were decreased at appropriate doses of both drugs (for some birds only the 3 mg/kg dose of *d*-amphetamine decreased high rates of responding), with the proportional extent of rate decrease directly related to control response rate.

Details of the effects on local responding in the tandem DRL components differed for the two drugs. Pentobarbital increased response rates throughout these intervals and generally produced approximately equivalent proportional rate increases in the two components, with points describing these changes being nearly coincident. For *d*-amphetamine 0.3 and 1 mg/kg, on the other hand, responding in-

creased only during the early segments of the intervals; rates at the ends of the intervals (approximately 0.4 responses per second) were unchanged or decreased. Furthermore, rates of about 0.4 responses per second were generally increased less by *d*-amphetamine when they occurred in the tandem DRL components than when they occurred in the tandem DRH components, while for some birds (most notably Birds 63 and 181), equivalent rates of responding throughout the intervals were increased less by *d*-amphetamine 0.3 and 1 mg/kg when they occurred in the tandem DRL components than when they occurred in the tandem DRH components.

Disruption of performance of the DRL and DRH requirements. Since only pentobarbital markedly increased rates near the end of the interval in the tandem DRL components, it seemed likely that pentobarbital, but not *d*-amphetamine, would disrupt performance of the pause requirements for obtaining access to grain, and thus increase total session time. Figure 5 compares average total session time as a function of drug dose for *d*-amphetamine and pentobarbital. Average session time increased slightly but reliably in the tandem DRL component after all doses of *d*-amphetamine, indicating some disruption of DRL performance in spite of the drug's failure to increase average rates at the end of these intervals. Session time during tandem DRH components increased in a dose-related manner for pentobarbital. Session time also increased during the tandem DRH components at the largest dose of each drug. In all cases when session time increased, however, the birds lost no more than two available reinforcements per session, on the average, in either component.

DISCUSSION

Tandem DRH (40 msec) and tandem DRL (4, 5, or 6 sec) pacing requirements added to the food-delivery response of a 3-min fixed-interval schedule resulted in high (0.70 to 1.37 responses per second) and low (0.18 to 0.29 responses per second) overall response rates, respectively, during the intervals. This extends the findings of Blackman (1967, 1968), MacPhail and Gollub (1975), and Sanger and Blackman (1975), who have shown that pacing requirements influence overall rates of responding maintained under variable-interval

schedules. The pattern of responding that developed in the two schedule components was similar to that observed under simple fixed-interval schedules, in that a short pause followed each food delivery, then responding occurred at an increasing rate until food was again available (Figure 1). Slight differences in response patterning during the two components were due to longer pauses after reinforcer delivery in the tandem DRL components, as well as to some deceleration of responding toward the end of the intervals during these components.

Fig. 5. Drug effects on total session time. Average time spent with each schedule component in effect on control and drug days is shown separately for the tandem DRL (O—O) and tandem DRH (●—●) components. Brackets around control points are ± 1 S.D.

As predicted by previous experiments (*e.g.*, Dews, 1958, 1965; Rutledge and Kelleher, 1965), pentobarbital had effects on overall rates of responding that were compatible with a rate-dependency interpretation. The drug increased low overall rates in the tandem DRL components, and at appropriate doses, decreased higher overall rates in the tandem DRH components (Figure 2). Furthermore, these rate changes took place with equal densities of reinforcement maintaining the two different response rates. These results are consistent with those of MacPhail and Gollub (1975), who studied drug effects on different response rates maintained by equal reinforcement densities under tandem VI DRL schedules, and extend the generality of those findings to a new drug class as well as to a different schedule (tandem FI DRL).

In contrast, the effects of *d*-amphetamine on overall rates of responding were not entirely

consistent with a rate-dependency interpretation because the drug failed to increase substantially low overall rates in the tandem DRL components. The results for *d*-amphetamine, however, are also consistent with those reported by MacPhail and Gollub (1975). In neither study did this drug reliably increase rates below 0.5 responses per second which were influenced by DRL response-pacing requirements, but higher response rates were markedly decreased at appropriate doses (3 mg/kg in the present study). The present study extends the findings for *d*-amphetamine by more fully describing the influence of pacing requirements on drug effects.

The prevalence of rate dependency in determining drug effects was most apparent in a fine-grain analysis of drug effects on local responding during the fixed-intervals. As described previously (Kelleher and Morse, 1968), effects of both drugs were related in an orderly way to control responding (Figures 3 and 4) such that the extent of drug-produced increase in low rates was inversely related to control rate, while the extent of drug-produced decrease in relatively higher rates was directly related to control rate.

Certain effects of *d*-amphetamine, but not pentobarbital, were modified by pause requirements at the end of the fixed interval. Pentobarbital markedly increased responding during the tandem DRL components (Figure 2) and changed comparable low rates occurring in the two components to an approximately equivalent extent (Figure 3). In contrast, pause requirements modified the effects of moderate doses of *d*-amphetamine, since relatively low rates occurring at the ends of the tandem DRL intervals were not increased by drug, while comparable rates were increased when these occurred during the tandem DRH components. Furthermore, for some birds, rates throughout the intervals were increased less when they occurred in the tandem DRL components than when they occurred in the tandem DRH components. Apparently, the DRL requirement lessened or restrained the extent of rate increase produced by *d*-amphetamine, especially toward the end of the intervals. This may account for the drug's failure to increase substantially low overall rates of responding in these components. It is possible that rate changes produced by drug during the tandem DRH components were also affected

by the pacing requirement, and contributed to the differential effect of drug in the two schedule components when these occurred. Pacing requirements may well have influenced the direction or extent of drug-produced rate changes in MacPhail and Gollub's (1975) study as well, but it is not possible to evaluate this because drug effects could not be compared on equivalent rates maintained under different pacing schedules.

Attenuation of rate-increasing effects of *d*-amphetamine might represent an adjustment to reinforcement loss, since rate increases produced by drug near or after the end of the tandem DRL components would make food delivery less probable. This does not seem likely, however, since pentobarbital markedly increased rates near the ends of these intervals without producing substantial reinforcement loss. Rather, the pause requirements themselves, interacting with rates and patterns of responding generated by the schedule contingencies, seem to be responsible for the modified drug effects observed.

The rate-dependent effects of drugs on local responding within the fixed intervals were apparent in the present study when very dissimilar overall rates of responding were maintained by equal densities of reinforcement delivery, and thus were independent of reinforcement density. Furthermore, these rate-dependent drug effects were apparent even when the extent of rate change produced by *d*-amphetamine was modified by response-pacing requirements. This latter result is similar to other reports where the extent of rate increase produced by drugs has been modified by a variety of dissimilar environmental events, including electric-shock delivery (McMillan, 1973), intensity of a light stimulus controlling behavior (McKearney, 1970), signaling food availability (Laties and Weiss, 1966; Thompson and Corr, 1974), but no disruption of the orderly relationship between drug effect and control response rate has occurred. Control rate of responding thus emerges as a powerful determinant of drug effects, a determinant independent of reinforcement density. Environmental influences on behavior and the specific characteristics of stimuli and schedules controlling behavior can, however, play important roles in determining the direction and extent of some drug-produced rate changes.

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