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A DETAILED ANALYSIS OF THE EFFECTS OF d-AMPHETAMINE ON BEHAVIOR UNDER FIXED-INTERVAL SCHEDULES[1]

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Pigeons were exposed to fixed-interval schedules of food reinforcement with durations of 300 sec, 100 sec, or 40 sec. A range of doses of *d*-amphetamine was administered to each pigeon, and the resulting behavior was analyzed at several levels of detail. Average rates in different portions of the intervals predicted the magnitude of the drug's effect, but a finer analysis showed that average rates did not adequately characterize the behavior in some parts of the intervals. The probability of responding in different parts of an interval without drug was also a good predictor of the magnitude of the effect of *d*-amphetamine, and at the same time was more descriptive of the interval-to-interval performance. Analyses of the control performance indicated that responding in individual intervals could be described as consisting of two parts: a very low, or zero, rate at the beginning of the interval followed by an abrupt transition to a slightly, but reliably, positively accelerated rate maintained until reinforcement.

Fixed-interval (FI) schedules of reinforcement have been used widely in the study of the effects of pharmacological agents on behavior. A fixed-interval schedule specifies that the first response that occurs after a fixed period of time will be reinforced. Responses that are reinforced under FI schedules show cyclic variations in rate of emission, so an adequate description of the performance under such schedules requires a description of the temporal pattern of responding as well as measures of overall response rate.

To portray changes in response rates, investigators frequently divide the fixed interval into a number (often 10) of segments of equal duration, and then compute the average rate in each of these segments over several repetitions of the fixed interval. The usual result of such an analysis is that a plot of average rate in a segment against the ordinal position of the segment is a monotonically increasing function, *i.e.*, average rates are very low in early parts of the fixed interval, and gradually increase as the interval progresses.

Dews (1964) suggested that the mean rates that occur at different times in fixed intervals could be used to examine the interaction between drugs and response rates. In earlier work (Dews, 1955), he had shown that the effects of pentobarbital on responding depended not only on dose, but also on the schedule of reinforcement that controlled the behavior. Specifically, the dose-effect curve for behavior under a schedule that controlled a high rate of responding (fixed ratio) differed from the curve under a schedule that controlled a much lower rate (fixed interval). Dews (1964) attempted to relate the effects of amobarbital on responding at different times in a modified fixed-interval schedule to the response rates that normally occurred at those times in the schedule without drug, and he found a strong relationship between local rates at different times in the fixed interval and the effects of amobarbital on response rate. Specifically, the change in response rate in different parts of a fixed interval depended on the control rate of responding in that segment of the fixed interval. The logarithms of

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change in rate plotted as a straight line against logarithms of control rate.

In later work, McMillan (1968*a*, *b*; 1969) showed that the effects of a variety of treatments with sympathomimetic amines also depended on control rate. Late in the interval when the response rate is usually high, drugs either did not change the rate or decreased it, whereas in the early and middle portions of the interval, where low and moderate rates prevail, sizeable increases in rate were obtained under drug conditions.

Kelleher and Morse (1968) discussed the dependence of drug effects on baseline rate, and have shown that "rate-dependent" drug effects are quite general. They reviewed data that showed the strong relationship between average control response rates in different parts of fixed intervals and the effects of drugs.

Recent analyses of fixed-interval responding in pigeons have questioned the accuracy of describing the performance in individual intervals as showing increases in average rate across the interval. Instead, these analyses have shown the performance to consist of a period of very low, or zero, rates of responding followed by an abrupt transition to a high, constant rate until reinforcement occurs (Schneider, 1969; Shull and Brownstein, 1970). This "two-state" analysis implies that within any one fixed interval only two rates occur. Schneider (1969) has shown further that the point of transition from the low to high rate varies from interval to interval. Thus, if the interval is divided into equal segments and then rates are averaged in these segments over several repetitions of the interval, a function is obtained in which the *average* rate increases gradually through the interval.

The present experiments were conducted in order to examine explicitly the implications of a "two-state" analysis of responding under fixed-interval schedules. This detailed analysis would show also whether there are limitations on using fixed-interval schedules to examine the rate-dependent effects of drug-behavior interactions.

METHOD

Subjects

Nine adult, male White Carneaux pigeons were used. All but Pigeon 121 were experimentally naive. Pigeon 121 had been exposed previously to a variety of procedures and had also been administered *d*-amphetamine. The pigeons were maintained at approximately 80% of their free-feeding weights (shown in Table 1), and were kept in individual cages in which they had free access to water and grit. They were given vitamin supplements daily.

Apparatus

Two chambers were used. One was a modified picnic ice chest with a compartment for the subject that measured 32 cm by 28 cm by 34 cm, and had a single response key (Ralph Gerbrands Co., 1.9-cm diameter) centered on one wall, 24.5 cm from the floor. A rectangular aperture through which mixed grain could be made available was located 9.0 cm below the key. The second chamber was a commercially available (Foringer, Model PH-004) three-key conditioning chamber for pigeons. Only the center key, 25.5 cm from the floor, was used for the present experiments. In both chambers, a force of 12 g (0.12N) was required to operate the key.

Experimental contingencies were arranged by solid-state circuitry (K-logic, Digital Equipment Corporation) located in an adjoining room, and data were recorded on electromechanical counters, cumulative response recorders, and occasionally on magnetic computer tape. White masking noise was provided in the room where the chambers were located.

Procedure

The pigeons were divided into three groups of three pigeons each. Pigeons 19, 20, and 121 and Pigeons 292, 294, and 295 worked in the picnic chest, whereas Pigeons 277, 288, and 290 worked in the other chamber. The key in the picnic chest was lighted green during a session, and the key in the standard chamber was lighted white. Two additional lights (houselights)were on during sessions for the pigeons in the second chamber. Illumination in the picnic chest was provided by only the green light behind the key.

The experimentally naive pigeons were trained to eat from the food hopper and then trained to peck the lighted key by shaping (reinforcement of responses successively approximating a key peck). The reinforcer was 3-sec access to mixed grain, and when grain was

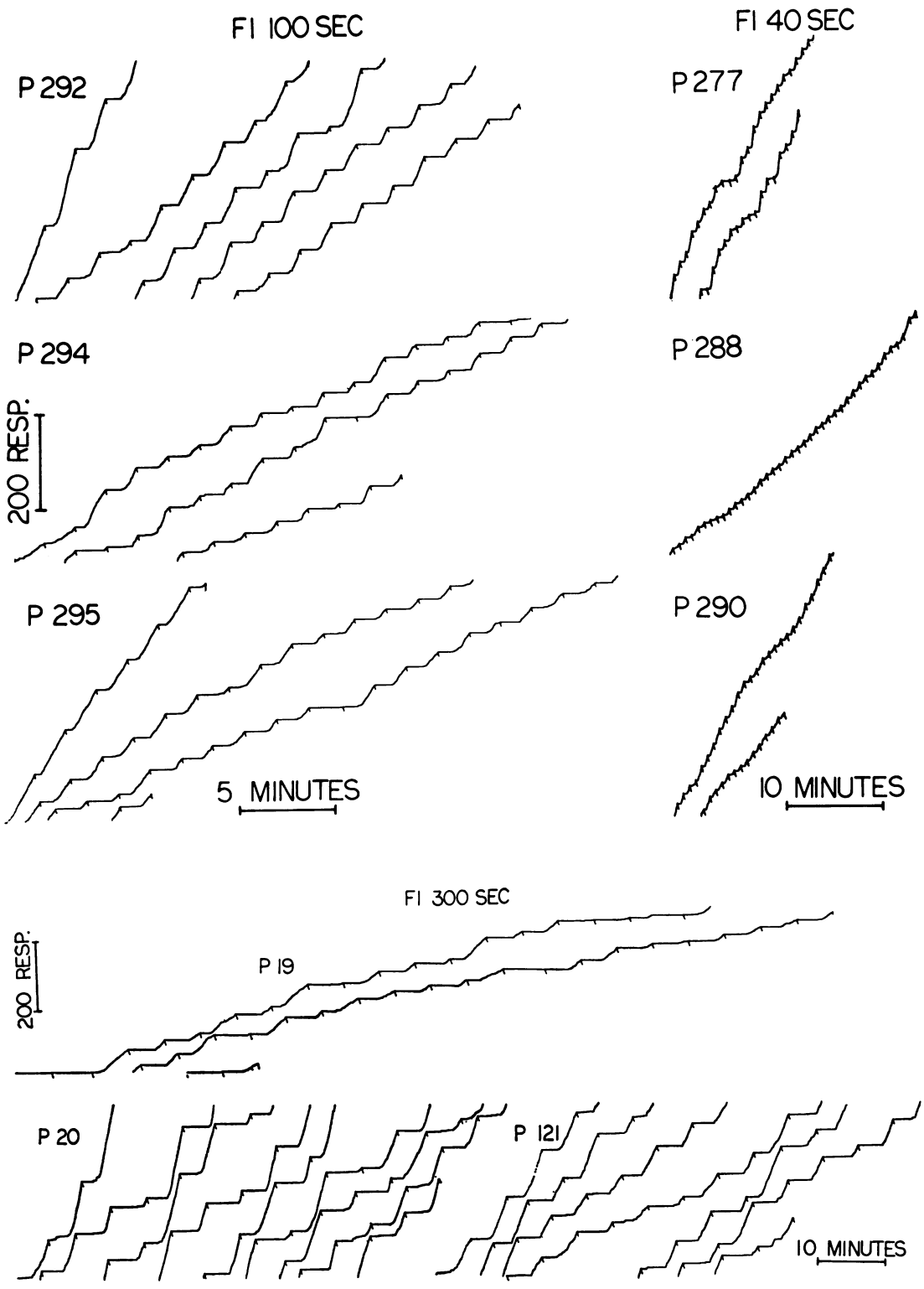

Fig. 1. Cumulative response records for all nine pigeons. The time axes have been collapsed for compact presentation. Note that the scales were not the same for all groups of pigeons.

presented, all lights in the chamber were extinguished except for a 1.2-W lamp that illuminated the grain. After one session of training under a fixed-ratio one response schedule, the pigeons were placed under the respective fixed-interval schedules.

Each group of pigeons was exposed to a different fixed-interval schedule of reinforcement. For Pigeons 19, 20, and 121, the first peck on the response key after 300 sec had elapsed since either the last presentation of grain or the beginning of a session produced access to grain (FI 300-sec). For Pigeons 292, 294, and 295 the schedule was FI 100-sec, and for Pigeons 277, 288, and 290 the schedule was FI 40-sec. Forty food deliveries constituted a session, which was held daily.

The FI 300-sec group received 190 sessions, the FI 100-sec group 89 sessions, and the FI 40-sec group 92 sessions of exposure to the fixed-interval schedule before drugs were administered.

d-Amphetamine sulfate was dissolved in physiological saline, and injected in a volume of 0.5 ml into the pectoral muscle 30 min before a session. The drug was always administered in a fixed quantity, independently of body weight, and doses were given in an irregular order. To allow the reader to convert these values to mg/kg, Table 1 gives the weight at which each pigeon was maintained (80% weight in grams). At least four days intervened between injections, and the effects of injections of saline were also examined. On the day of, and the day before each injection, data were recorded on magnetic computer tape in the following way. The number of pecks occurring in each second of the fixed interval, and reinforcements, were recorded. Thus, a second-by-second record of responding within each fixed interval was obtained. These data were later analyzed with the aid of a digital computer.

RESULTS

All pigeons showed characteristic performance under the fixed-interval schedules. Figure 1 shows representative cumulative response records for each of the pigeons under control conditions. The records are similar in appearance to those that are generally observed when fixed-interval schedules are used (*cf.* Ferster and Skinner, 1957).

Quantitative analyses of the data were made at several levels of detail. First, drug effects on two overall measures of performance, overall rate and the Mathematical Index of Curvature (Fry, Kelleher, and Cook, 1960), were examined. Next, the effects of *d*-amphetamine on average local rates within the fixed intervals were determined, followed by an analysis of these local rates on an interval-by-interval basis. Two analyses were then directed at determining whether or not response rate accelerates in individual repetitions of fixed intervals. A final analysis examined the relationship between an interval-by-interval performance measure and a measure that represents a session average.

Drug Effects on Overall Measures

Table 1 presents the data for overall response rates. The rates were calculated using data only from within each fixed-interval period, *i.e.,* time and responses after reinforcement became available in each fixed interval were not included. Exclusion of time after the fixed interval elapsed resulted in one point that is not representative of the actual performance for Pigeon 288 under a 2.00-mg dose of *d*-amphetamine. The value in the table indicates that 2.00 mg of *d*-amphetamine increased overall response rate. Actually, this dose of drug suppressed all pecking in Pigeon 288 for about the first 25 min of the session, after which response rate was quite high.

The variability in the control values that were taken from sessions preceding those in which injections were given, is not representative of the session-to-session variability, except for Pigeon 277. For the other pigeons, there were long-term drifts in baseline response rate, and since the dose-response curves were obtained over a period of several months, control values for different doses are often quite different. The changes in overall rate from session to session were, however, usually quite small.

The effects of *d*-amphetamine on overall response rate were varied. Large increases in response rate at intermediate doses were seen in Pigeons 288 and 292, whereas moderate increases at these doses were observed in Pigeons 121, 294, and 295. The overall rates of the other pigeons were not increased significantly by *d*-amphetamine. The behavior of the three

Table 1

Overall response rates (responses per minute) in control and drug sessions.

Pigeon	80% Weight (g)	Dose (mg)	Control	Drug	Drug/ Control
19	444	Saline	9.0	6.5	0.72
(FI 300-sec)		0.125	5.1	6.2	1.22
		0.125	5.8	7.2	1.24
		0.25	6.4	4.8	0.75
		0.50	18.3	10.0	0.55
		1.00	11.8	8.8	0.74
20	492	Saline	44.0	44.0	1.00
(FI 300-sec)		0.125	48.1	47.4	0.98
		0.25	51.7	53.5	1.03
		0.50	39.3	45.2	1.15
		0.50	38.8	52.8	1.36
		1.00	48.8	47.3	0.97
		1.50	51.3	13.3	0.26
121	435	Saline	21.8	22.8	1.05
(FI 300-sec)		0.125	23.5	27.5	1.17
		0.25	30.4	55.0	1.81
		0.25	23.4	37.2	1.59
		0.50	30.9	44.6	1.44
		0.50	23.7	44.0	1.86
		1.00	28.4	21.1	0.74
292	419	Saline	32.2	29.0	0.90
(FI 100-sec)		0.125	35.4	62.7	1.77
		0.25	40.5	65.2	1.61
		0.50	55.9	78.3	1.40
		0.50	46.2	138.0	2.99
		1.00	39.5	97.7	2.47
		2.00	64.1	75.4	1.18
		4.00	57.8	35.4	0.61
294	432	Saline	19.8	15.6	0.79
(FI 100-sec)		0.125	16.2	32.7	2.02
		0.25	19.6	37.1	1.89
		0.50	18.3	28.4	1.55
		1.00	18.9	36.1	1.91
		2.00	13.5	35.1	2.60
		4.00	14.6	37.2	2.55
295	499	Saline	20.5	21.8	1.06
(FI 100-sec)		0.125	18.9	23.2	1.23
		0.25	21.3	31.6	1.48
		0.50	32.2	37.5	1.16
		0.50	23.2	37.6	1.62
		1.00	28.1	24.3	0.86
		2.00	38.2	42.5	1.11
		4.00	30.7	24.7	0.80
277	406	Saline	35.1	47.1	1.34
(FI 40-sec)		Saline	53.9	58.8	1.09
		0.125	48.4	55.2	1.14
		0.25	34.5	36.1	1.05
		0.50	42.8	26.3	0.61
		0.50	62.6	27.2	0.43
		1.00	22.8	0.0	0.00
288	457	Saline	19.1	23.6	1.24
(FI 40-sec)		0.125	19.2	25.3	1.32
		0.25	17.6	21.8	1.24
		0.50	17.4	42.0	2.41
		0.50	21.1	53.7	2.55
		1.00	25.4	39.5	1.55
		2.00	22.9	36.6	1.60
290	450	Saline	41.7	51.4	1.23
(FI 40-sec)		0.125	35.1	31.9	0.91
		0.25	27.3	26.4	0.97
		0.50	29.1	33.4	1.15
		0.50	25.3	25.8	1.02
		1.00	29.3	29.9	1.02
		2.00	25.8	0.0	0.00

pigeons under the FI 100-sec schedule was quite resistant to any rate-decreasing effects of high doses of *d*-amphetamine. Generally, the dose-effect curves were inverted U-shaped functions.

The disruptive effects of *d*-amphetamine on the temporal pattern of responding were somewhat more consistent across pigeons than were the effects on overall response rate. The effects of *d*-amphetamine on a Mathematical Index of Curvature (Fry *et al.*, 1960) are shown in Figure 2. The Index would be zero if response rate were constant through each interval, and positive if there were an overall pattern of positive acceleration of responses. An Index of Curvature was calculated for each fixed interval in control and drug sessions. The points in Figure 2 represent the means of the indexes of individual intervals over a session. The control values were taken from the sessions immediately preceding sessions in which drugs were administered. *d*-Amphetamine reduced the Index of Curvature below control levels for all pigeons. When the fixed interval was 300 sec or 40 sec, the decreases in the Index were dose-related, larger doses producing larger decreases in the index. The pattern of effects was different for the pigeons in the FI 100-sec group. The behavior of these three pigeons showed great sensitivity to low doses of *d*-amphetamine on this measure. The smallest dose, 0.125 mg, produced substantial decreases in the index for two of the pigeons, and increasing doses of *d*-amphetamine did not produce larger decreases in the index.

Drug Effects on Local-Rate Measures

In order to analyze the changes in patterns of responding, the fixed intervals were subdivided into 10 equal segments, and the effects of *d*-amphetamine on the average response rate in each tenth of the interval were ex-

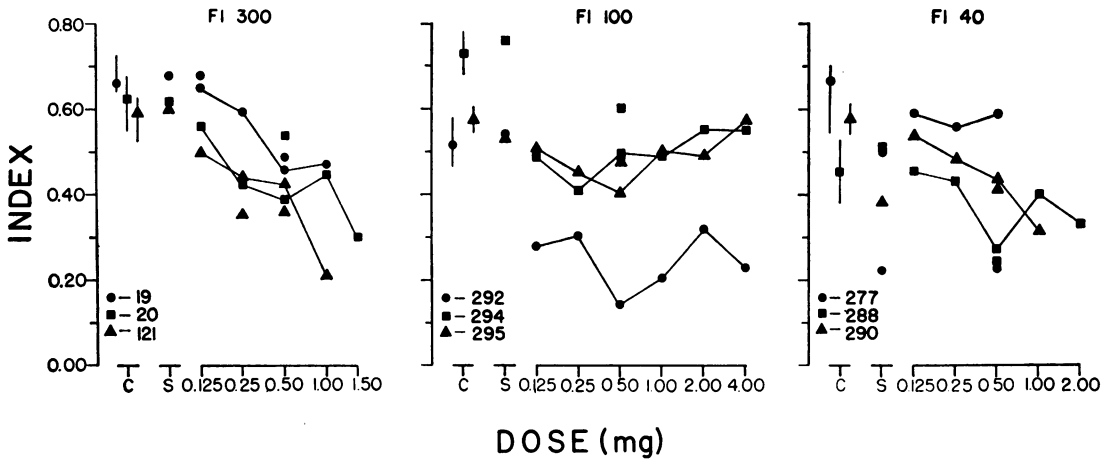

Fig. 2. A Mathematical Index of Curvature as a function of dose of *d*-amphetamine sulfate. The points above "C" are the means of the control values, and the vertical bars indicate the ranges of control values. The points above "S" are from sessions in which saline was administered, and unconnected points are from second determinations.

amined. Some results of this analysis are presented in Figures 3, 4, and 5. These figures are scatterplots in which the logarithms of the response rate (responses per minute) in individual tenths of the fixed interval under drug conditions are plotted against the logarithms of the response rate in the corresponding tenths of the fixed interval under control conditions. The straight lines were fit by eye, and control response rates were taken from the session immediately preceding the session in which the drug was given. It is important to remember that the points shown in Figures 3, 4, and 5 are averages, *i.e.*, each point represents the rates in a particular tenth of each fixed interval averaged over 40 repetitions of the interval.

Generally, points in the left portions of these figures describe behavior occurring early in the fixed interval when control response rates are usually low, whereas points in the right portions of the figures represent average rates later in the fixed interval when control rates are generally higher. In these figures, the positive diagonal is the line of no effect, *i.e.*, if the response rates in each tenth under drug conditions were the same as the rates under control conditions then the points would lie on this line. Points above the diagonal indicate response rates that are elevated under drug conditions, and points below the diagonal occur when average rates are decreased under drug conditions.

Under the three schedule parameters, *d*-amphetamine proportionately increased the average response rates early in the interval much more than it increased rates later in the interval. This differential effect of the drug is seen most dramatically in Figure 3 for the 1.00-mg dose for Pigeon 121 (FI 300-sec) and in Figure 4 for the 4.00-mg dose for Pigeon 292 (FI 100-sec). For these two pigeons under these two doses, *d*-amphetamine increased the low average rates occurring early in the interval, and at the same time lowered the higher average rates occurring later in the interval. The effects of *d*-amphetamine, then, on the average rates of responding in each tenth were correlated with the control response rates in those tenths.

An Interval-by-Interval Analysis of Drug Effects on Local Rates

The effects of *d*-amphetamine on response rates at different times within the fixed intervals were examined further on an interval-by-interval basis. Figure 6 will aid in explaining this analysis. The upper portion of the figure shows control data from Pigeon 121 (FI 300-sec). Plotted are the mean rates of responding in each tenth of the fixed interval. Each point is the mean of the 40 occurrences of that tenth of the fixed interval. The figure shows that the average rate of responding increased through the fixed interval. Such a plot might be called an "average scallop". The

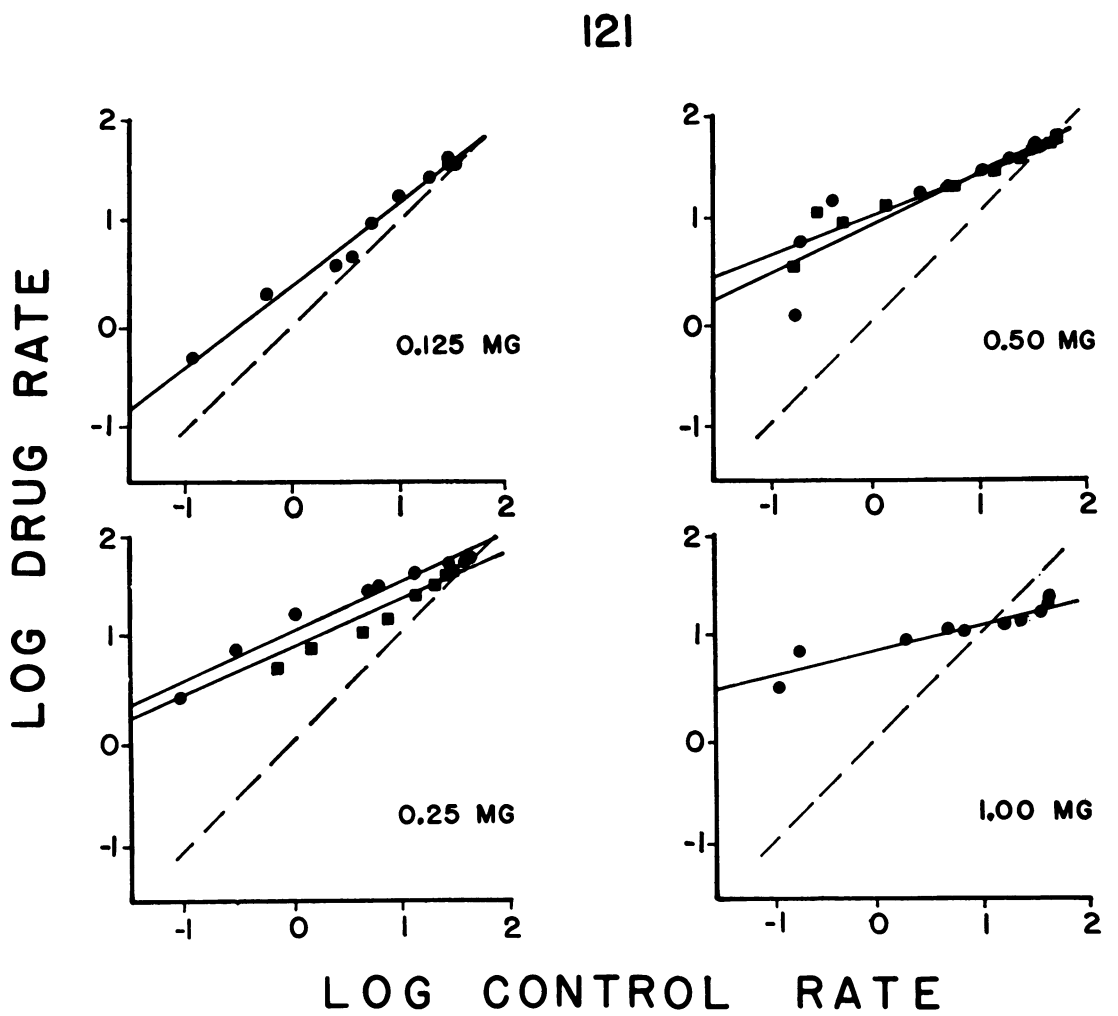

Fig. 3. Scatterplots of logarithms of rates in each tenth of the FI 300-sec schedule for Pigeon 121. Each point represents the intersection of the logarithms of the control rate in a particular tenth of the interval (abscissa) and the logarithm of the rate under drug conditions in the same tenth of the interval (ordinate). The lines were fit by eye, and the squares represent second determinations. The dashed line is the line of no effect. Scatterplots from each dose administered are shown.

lower three graphs in Figure 6 are frequency histograms. Each histogram shows the frequency of occurrence of a specific range of response rates in a given tenth of the fixed interval. The class intervals in these histograms are two responses per minute wide except for the first (leftmost) bin, which denotes the frequency of occurrence of a rate of zero responses per minute. The leftmost histogram shows that during the first tenth of the fixed interval, Pigeon 121 once had a rate of three or four responses per minute and in the other 39 intervals in the session did not peck. The middle histogram is from the sixth tenth (*i.e.*, from 151 through 180 sec) of the fixed interval. During 20 of the 40 repetitions of the interval, Pigeon 121 made no pecks during this tenth, and on 10 occasions responded at a rate greater than 37 responses per minute. Note that the number of occurrences in the histogram for the sixth tenth of the interval does not total to 40. This is because response rates from the sixth tenth that occurred as a result of the pigeon's beginning to respond during the sixth tenth of a particular interval were excluded. To determine whether a transition from not pecking (pausing) to pecking occurred in a given tenth, the

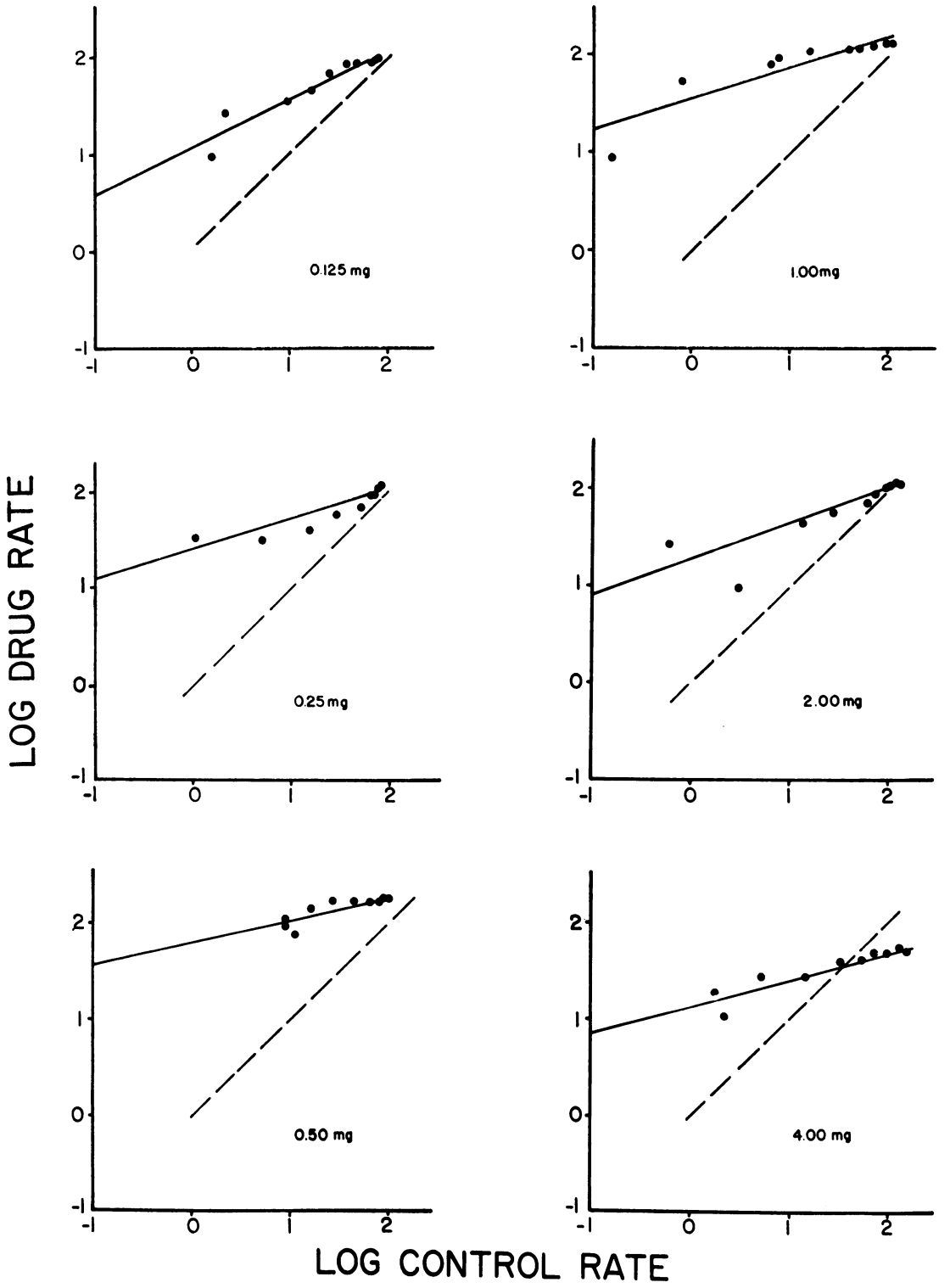

Fig. 4. Scatterplots of logarithms of response rates in each tenth of the FI 100-sec schedule for Pigeon 292. See Figure 3 for explanation.

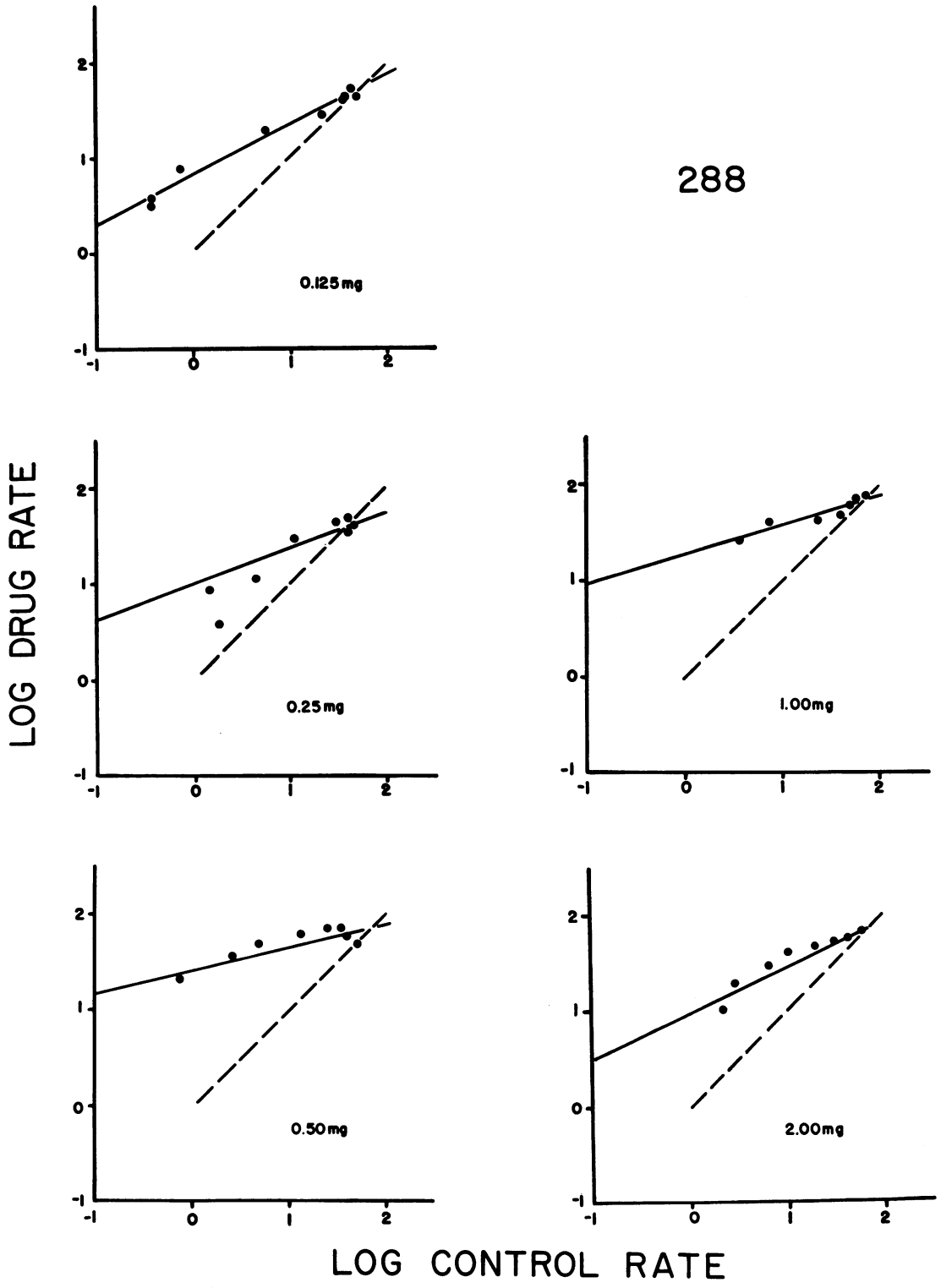

Fig. 5. Scatterplots of logarithms of response rate in each tenth of the FI 40-sec schedule for Pigeon 288. See Figure 3 for explanation.

following analysis was made for each presentation of the fixed interval. The response rates in each tenth were scanned from the end of the interval to the beginning. When the scan produced a tenth in which no responses had occurred, the following tenth was designated as the tenth in which the transition took place. For example, if the fifth tenth was the first one found by the backwards scan to contain no responses, then the sixth tenth was designated as the tenth in which the transition from pausing to pecking took place. Response rates from tenths of the interval that contained the transition were not included in the frequency histograms because these rates would represent an average of periods of not responding and responding. For example, they might represent 20 sec of pausing followed by 10 sec of responding at a rate of 60 responses per minute, yielding an average rate of 20 responses per minute that hardly represents the actual performance.

Returning to the discussion of the center frequency histogram of Figure 6, note that the mean rate from the sixth tenth, as shown in the upper figure, was about 20 responses per minute, yet the frequency histogram shows that a response rate of 20 pecks per minute did not occur in the sixth tenth of any interval represented in the histogram. The right-hand histogram shows the frequencies of occurrence of various response rates during the tenth tenth of the fixed interval. During most occurrences of this tenth, the response rate was greater than 37 responses per minute.

Analyses such as that shown in Figure 6 suggested that the gradual increase in average response rate through a fixed interval is a reflection of an increasing probability of responding at a relatively high rate as the interval progresses.

Figures 3, 4, and 5 showed that average response rates early in the interval were generally increased by *d*-amphetamine. Frequency histograms of rates for each tenth of the interval under drug conditions were examined

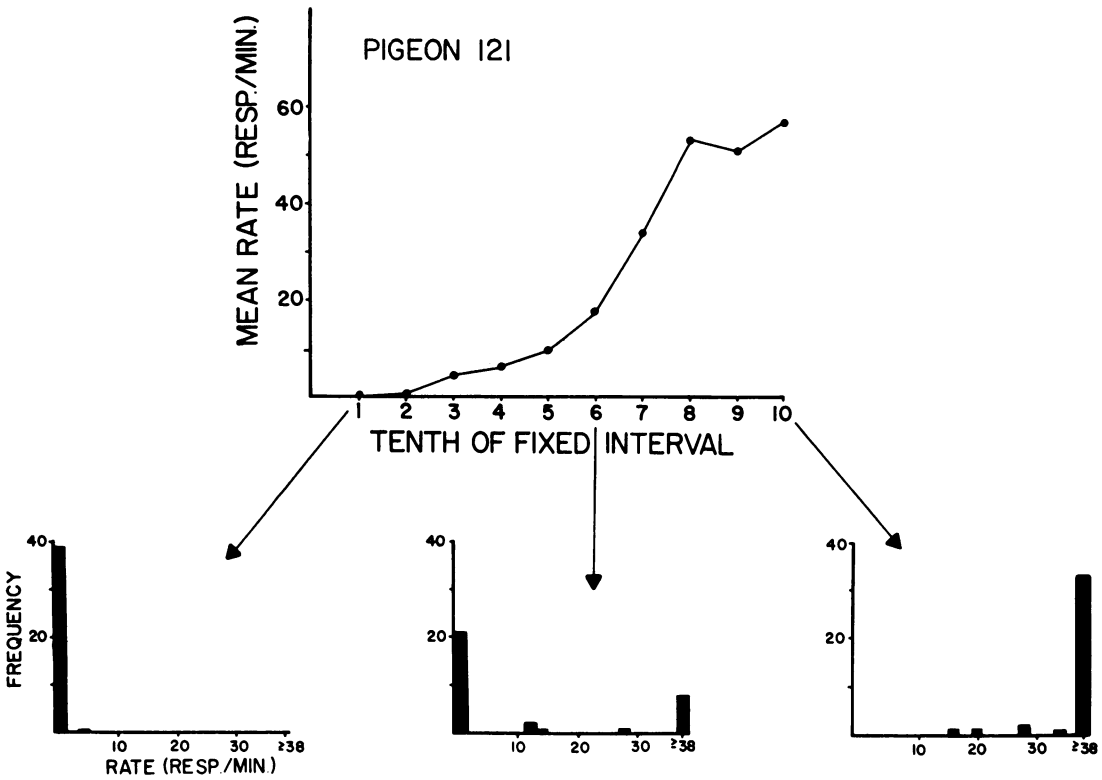

Fig. 6. The upper figure shows mean response rate in each tenth of the FI 300-sec schedule in one session for Pigeon 121 under control conditions. The lower three frequency histograms show the frequencies of occurrence of specific rates in the first, sixth, and tenth tenths of the interval. The frequencies were obtained from the 40 repetitions of the interval in a session. See text for further explanation.

to determine in more detail the nature of these increases. Figures 7 and 8 show frequency histograms of rates for two of the pigeons in the FI 300-sec group under two different doses of *d*-amphetamine. The histograms from the control sessions show marked bimodality in the middle portions of the fixed interval, indicating that the average response rates for these tenths were determined by a combination of times when the animal was not responding at all with times when the animal was responding at a relatively high rate. The effects of *d*-amphetamine on responding in early parts of the fixed interval consisted of decreasing the number of times in a session that the pigeons paused during these early tenths. It is also apparent that under drug conditions these two pigeons emitted intermediate rates of responding with a much higher frequency than under control conditions. The effects for the other pigeons under the other parameter values were qualitatively similar.

Because of the small class intervals used in the histograms in Figures 7 and 8, the effects of *d*-amphetamine on the distributions of response rates in later portions of the interval are not shown clearly. Figure 9 shows distributions of response rates in the last tenth of the fixed interval for one pigeon from each of the three groups. Each histogram is from a single session, and the class intervals have been enlarged considerably, compared to those in Figures 7 and 8. Perhaps the most striking information in Figure 9 is in the histograms of the control performance. The pigeons almost always responded during the last tenth of the interval, but the variability in rate over the last tenth was very great. The amount of variability in response rate shown in the histograms of the control performance is quite representative, not only of other control performances of Pigeons 121, 290, and 295, but also of the performances of the remaining pigeons. High doses of *d*-amphetamine often shifted the distribution to the left, and also

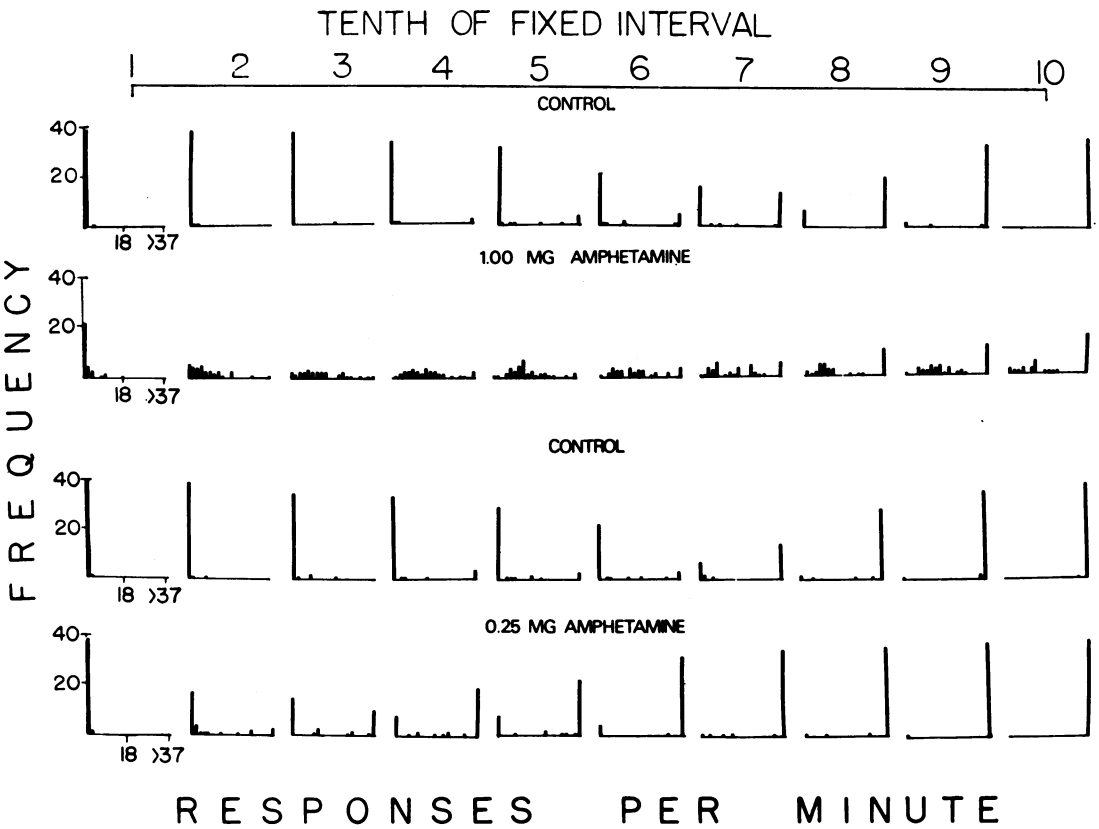

Fig. 7. Frequency histograms of occurrences of classes of response rates in each tenth of the fixed interval for two control and two drug sessions for Pigeon 121.

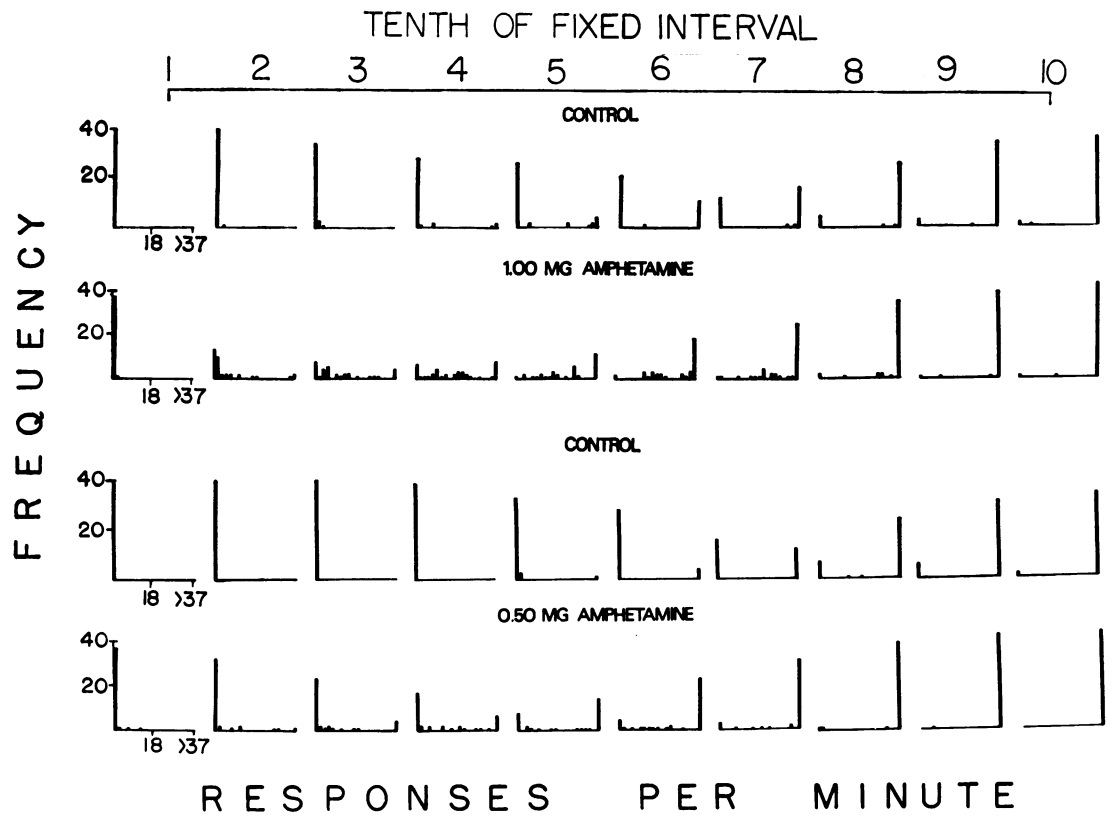

Fig. 8. Frequency histograms of occurrences of classes of response rates in each tenth of the fixed interval for two control and two drug sessions for Pigeon 20.

occasionally increased the variability in the distributions. Intermediate doses usually left the distributions unchanged, although in the histogram for Pigeon 295 under the 0.50-mg dose, a reduction in variability is shown.

The interval-by-interval analysis of the rates in each tenth of the fixed intervals showed that the mean rates of responding generally used to characterize performance were not very representative of the performance in the middle portions of the interval. The predictive power of the average rates, nevertheless, is substantial, as shown in Figures 3, 4, and 5. An attempt was made, therefore, to see whether some other aspect of the performance in each tenth of the interval could have comparable predictive strength, and at the same time be more representative of the interval-by-interval performance. The measure finally chosen was the probability that the pigeon responded at all in a given tenth of the interval.

The number of instances in which the rate was greater than zero was divided by the total number of entries in a histogram to yield a probability that the animal was responding in a particular tenth. These probabilities were computed for both control and drug sessions, and then scatterplots were made on logarithmic coordinates. Three sets of scatterplots are shown in Figures 10, 11, and 12. As in the scatterplots for response rate, each point represents the intersection of the probability value for a particular tenth of the interval under drug conditions and the probability value for the same tenth of the interval under control conditions. Again, the positive diagonal is the line of no effect, and points in the lefthand portions of the graphs represent data from early in the intervals when the probabilities were low, and points in the right part of each frame are from later in the intervals. The straight lines were fit by eye.

Generally, the lines describe the points well, and the pattern of effects is similar to that observed for response rates. The lower prob-

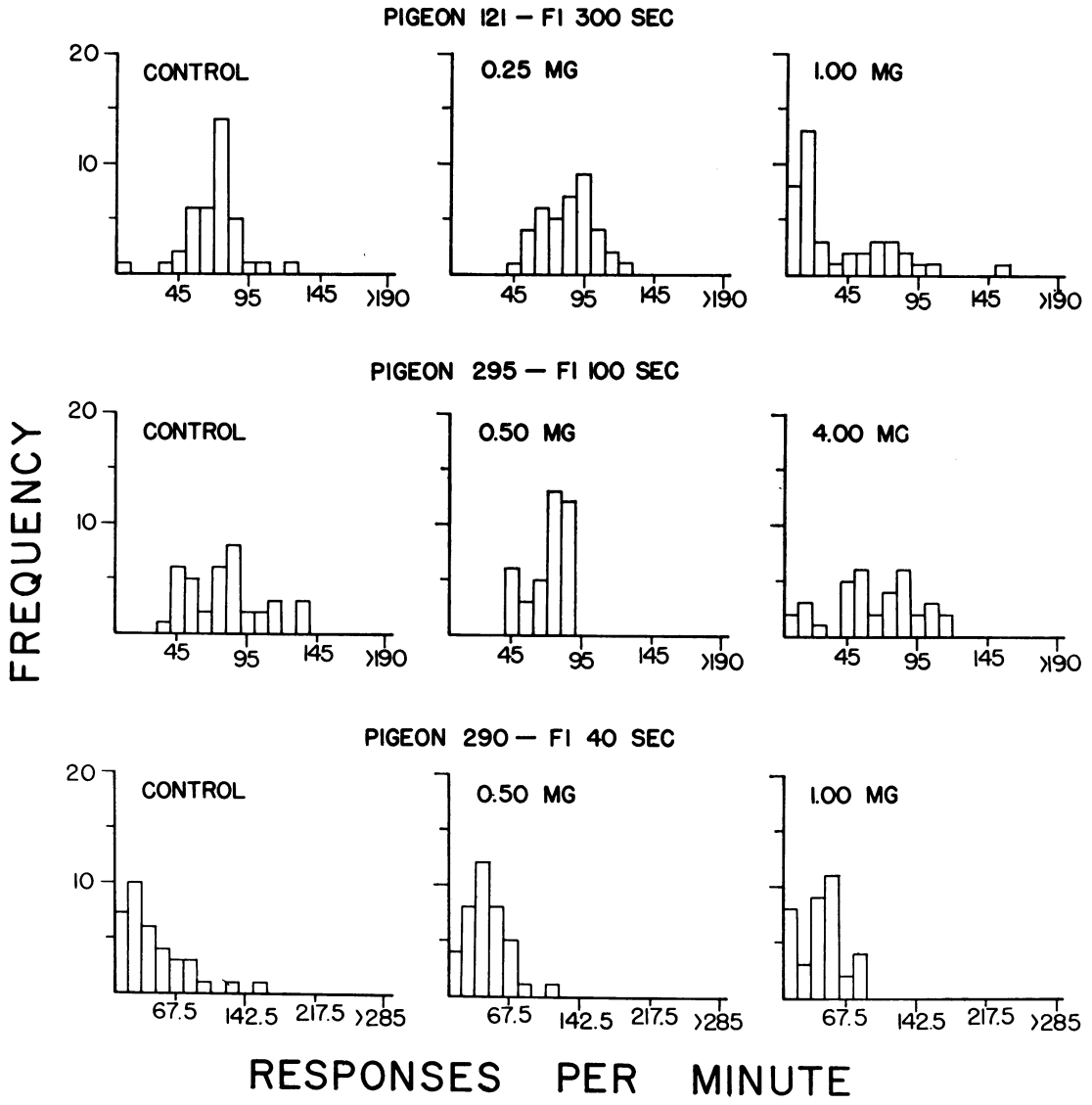

Fig. 9. Frequency histograms of classes of responses rates in the last tenth of the fixed intervals under control and drug conditions. Note that the abscissae for the bottom row of histograms differ from those for the other two rows.

abilities of responding early in the intervals are increased proportionately more than are the higher probabilities from late in the intervals. The main difference between these plots of probability of responding and the plots for average rates is that the latter functions sometimes cross the positive diagonal at high doses, indicating that the rates from late in the fixed interval are reduced. The functions for probability rarely crossed the positive diagonal, and thus did not always depict the rate-decreasing effects of amphetamine on response rates late in the intervals.

Drug Effects on Acceleration During Fixed Intervals

The analysis thus far has indicated that the gradually increasing intermediate rates in the middle of intervals shown in an "average scallop", such as in the upper portion of Figure 6, are due to a large extent to averaging periods of responding and not responding. The

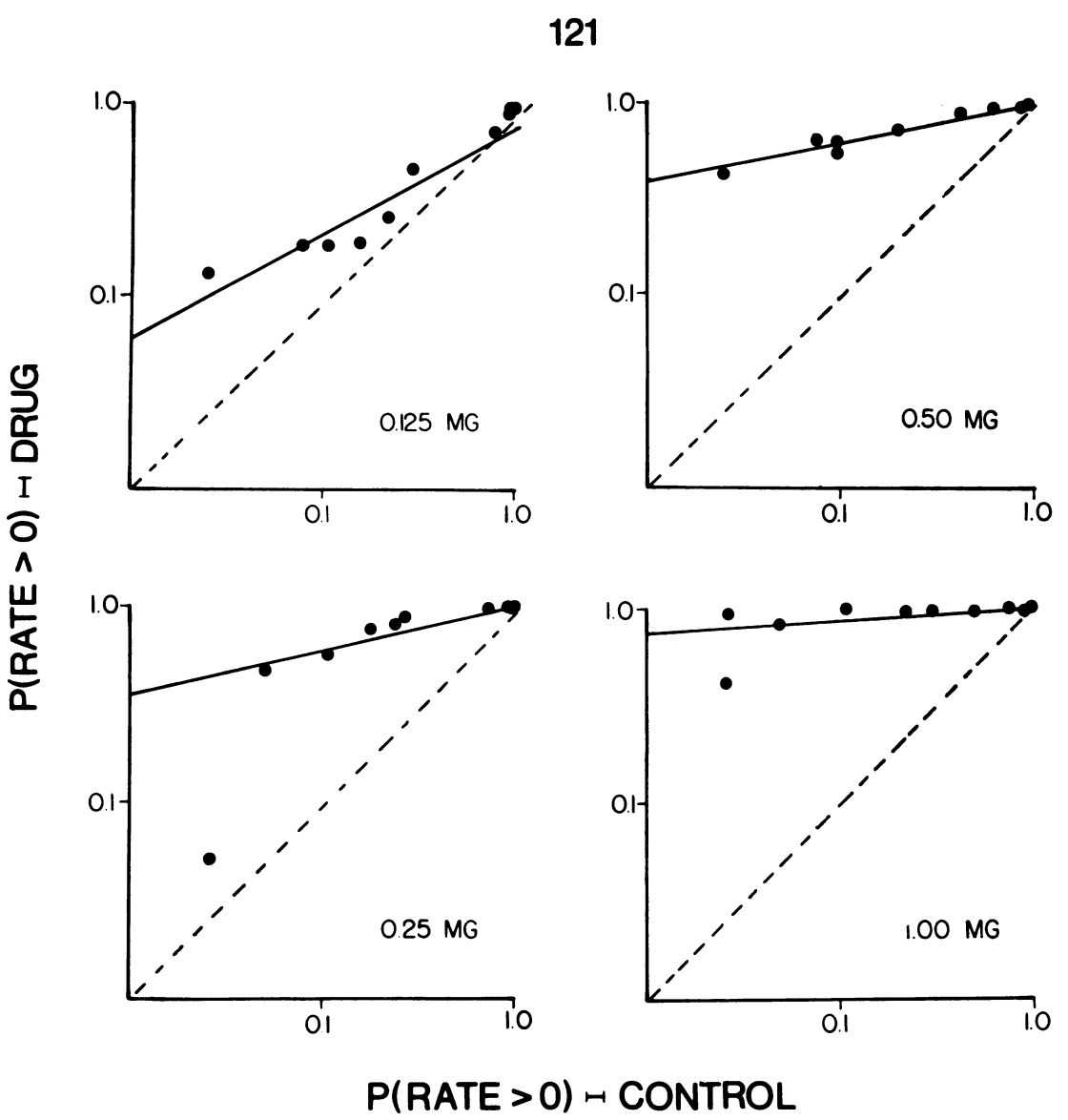

Fig. 10. Scatterplots of probability of responding in separate tenths of the FI 300-sec schedule for Pigeon 121. Each point represents the intersection of the probability under control conditions in a particular tenth of the interval (abscissa) and the probability under drug conditions in the same tenth (ordinate). The lines were fit by eye, and scatterplots from several doses are shown. Note that the coordinates are logarithmic.

question arises as to whether there was *any* positive acceleration of responding within individual fixed intervals, and, if there was, what were the effects of *d*-amphetamine on this acceleration? Two types of analysis were directed at this question.

The first analysis involved an estimate of the second derivative of the cumulative response record. To begin the analysis, the period of responding was defined as it was for the construction of the histograms, *i.e.*, each interval was scanned backwards, in tenths, for the first tenth that contained no responses, and the following tenth was designated as the one in which the transition from pausing to responding took place. The tenths after the tenth in which the transition occurred were defined as the period of responding in each interval. After determining the period of responding, successive differences in the num-

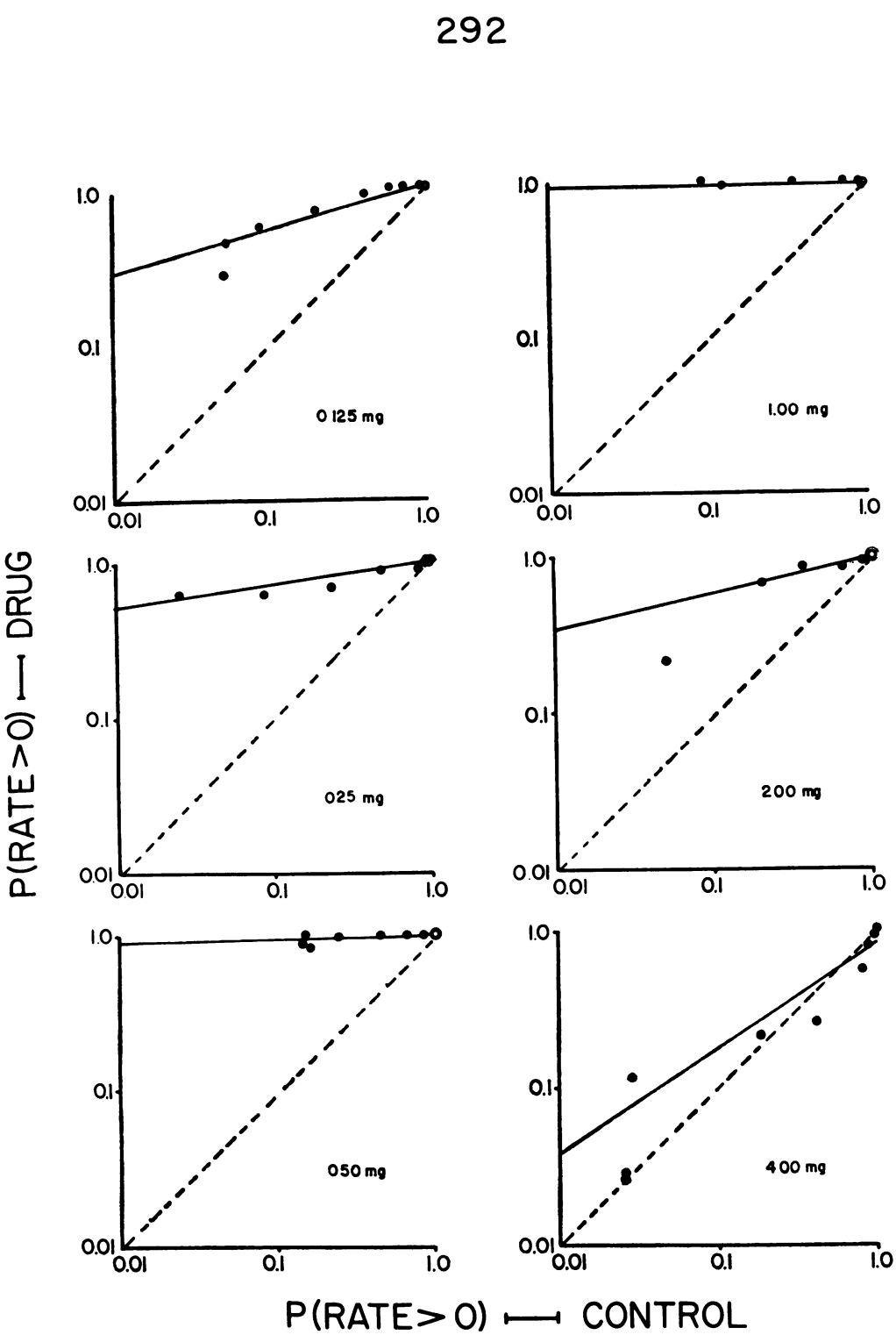

Fig. 11. Scatterplots of probability of responding in separate tenths of the FI 100-sec schedule for Pigeon 292. See Figure 10 for explanation.

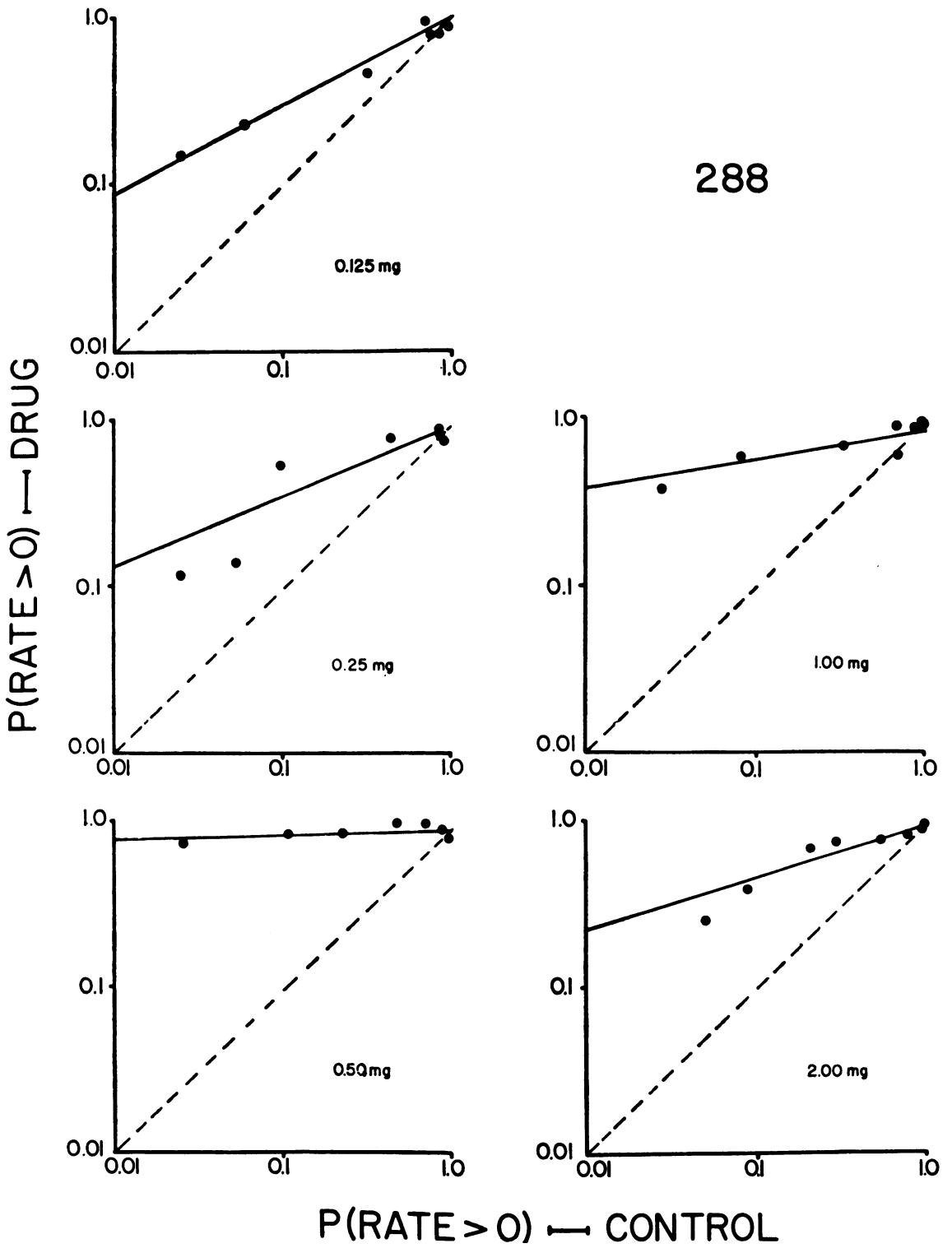

Fig. 12. Scatterplots of probability of responding in separate tenths of the FI 40-sec schedule for Pigeon 288. See Figure 10 for explanation.

bers of responses in each tenth were taken and then summed. For example, if the period of responding began in the sixth tenth of an interval (*i.e.*, the fifth tenth was the point of transition), then the number of responses in the sixth tenth was subtracted from the number in the seventh tenth and the difference was saved. Then, the number of responses in the seventh tenth was subtracted from the number in the eighth tenth and the difference added to the result of the first subtraction. The successive subtractions were continued until the number of responses in the ninth tenth was subtracted from the number in the tenth tenth, and the last addition was made. This analysis was performed on the data from individual intervals, and applied only to the period of responding. A further restriction was that only intervals in which the period of responding subsumed at least the last two tenths of the interval were included.

If the response rate during the period of responding were constant, then the sum of the differences should equal zero. A positive sum of the differences indicates that the rate during the period of responding was positively accelerated. The primary datum used in this analysis was the percentage of intervals in a session in which the sum of differences was positive. Figure 13 shows the results of this analysis for all pigeons. If the rate were nearly constant during the period of responding, then the expected percentage would be 50%. Figure 13 clearly shows that the control values, especially for the pigeons in the FI 300-sec and FI 100-sec groups, were well above 50%. The points that are filled indicate that the chance of obtaining such a proportion by chance if the rate were constant is less than 0.01 (z approximation to Fisher's Exact Probability Test). In addition to providing evidence of acceleration in the control performances, Figure 13 also shows that *d*-amphetamine had no systematic effect on the likelihood of acceleration.

A second type of analysis was conducted on the control performance only, and only with the three pigeons (19, 288, and 295) that showed the least amount of acceleration. It was possible to calculate mean rates for each tenth of the fixed interval, excluding those intervals in which no responding occurred in the particular tenth in question. That is, the mean response rates in each tenth, given that the rate was not zero, were computed. This measure, which shows how rapidly the pigeons pecked at different times in the intervals given that they were responding at all, is presented in Figure 14 averaged across all the control sessions. The function for Pigeon 19 is missing a point in the second tenth because this pigeon never responded during that tenth in

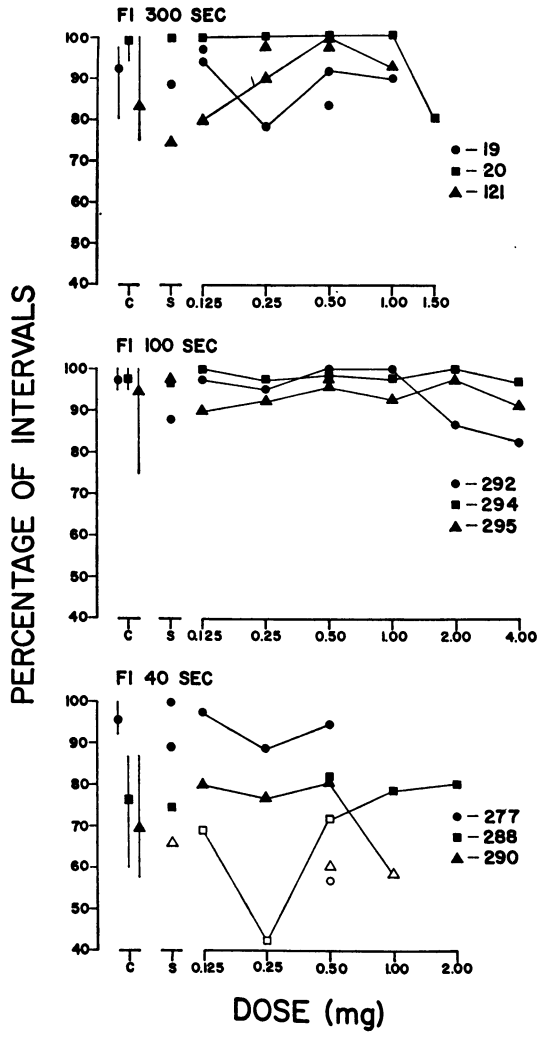

Fig. 13. Percentage of individual fixed intervals in which response rate during the period of responding was accelerated, as a function of dose of *d*-amphetamine sulfate. See text for description of how the periods of responding and acceleration were defined. The points above "C" are means of the control values, and the vertical bars indicate the ranges of the control values. The points above "S" are from sessions in which saline was administered. Unconnected points are from second determinations, and all filled points are significantly different from 50%.

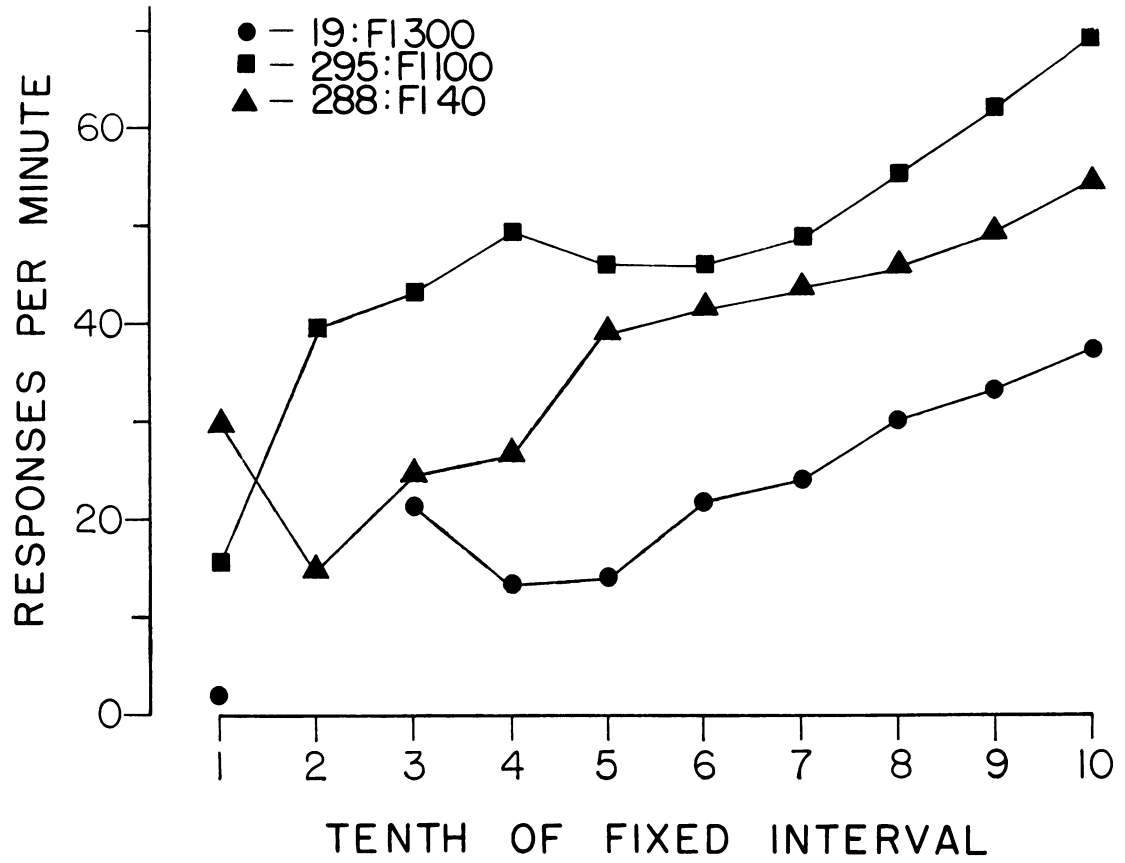

Fig. 14. Conditional mean rates of responding in different tenths of the fixed intervals for Pigeons 19, 288, and 295. The rates are averages from all control sessions, and were calculated excluding all instances in which no responding occurred in the specified tenth of the intervals, *i.e.*, the rates are mean rates given that the rate was not zero.

any control session. The functions for all three pigeons increase from left to right, indicating that the pigeons responded at higher rates later in the intervals.

Relationship Between Probability and Local-Rate Measures

The last two analyses show that acceleration in response rate did, in fact, occur under the fixed-interval schedules used here. The analyses presented earlier implied, however, that the acceleration shown in the "average scallop" was also due, in part, to averaging periods of pausing with periods of responding to produce intermediate average rates of responding. An attempt was made to evaluate the relative contribution to the average scallop of two factors: the time in the interval when the pigeon began responding, and the acceleration that occurred during the period of responding. The assumption was made for this analysis that these two factors were the only sources of variance in the response rates shown in the average scallop. For all individual control and drug sessions, then, the probabilities of responding in each tenth of the fixed intervals were determined as before, and were correlated with the average rates of responding in those same tenths of the fixed intervals. The Pearson Product-Moment Correlation coefficients (r) were then squared to give the proportion of the variance in the average scallop "accounted for" by probability of responding. The results of this analysis are presented in Table 2. The most obvious fact to be seen in the control values is that a very large amount of the variance was "accounted for" by probability of responding. Note also that the three pigeons chosen because they showed small amounts of acceleration during the period of responding, had the largest values of r^2 in their respective

Table 2

Proportion of Variance in Overall Scallop Accounted for by P (Rate > 0)

Pigeon	Mean of Control	Saline	Dose of d-amphetamine (mg) 0.125	0.25	0.50	1.00	2.00	4.00
277	0.920	0.910	0.823	0.982	0.986			
288	0.980	0.994	0.964	0.980	0.947	0.974	0.980	
290	0.968	0.949	0.955	0.908	0.952	0.970		
292	0.928	0.966	0.964	0.891	0.507	0.612	0.848	0.819
294	0.930	0.958	0.912	0.914	0.908	0.901	0.901	0.817
295	0.949	0.984	0.958	0.974	0.876	0.960	0.884	0.945
19	0.971	0.990	0.964	0.990	0.992	0.935		
20	0.925	0.927	0.781	0.799	0.748	0.566	0.641*	
121	0.983	0.988	0.986	0.918	0.792	0.428		

*Dose was 1.50 mg

groups. This difference indicates that the relative lack of acceleration during the period of responding resulted in a higher proportion of the variance in the average scallop that was attributable to probability of responding than there was in the data from the pigeons that showed more pronounced acceleration during the period of responding.

Administration of *d*-amphetamine did not systematically affect the value of r^2 across animals. The data from Pigeons 20, 121, and 292 are interesting in that intermediate doses of *d*-amphetamine decreased the proportion of variance accounted for by probability of responding, but as Figure 13 shows, these doses did not decrease the likelihood of acceleration during the period of responding.

DISCUSSION

The present results extend to shorter fixed-interval values the finding that the effects of *d*-amphetamine on average response rates in different portions of the interval depend on the corresponding average control response rate. Most previous research involving *d*-amphetamine and fixed-interval schedules has employed fixed intervals of 300 sec or longer (*e.g.*, Kelleher and Morse, 1968; McMillan, 1968 *a,b*), although shorter intervals have been used (*e.g.*, MacPhail, 1971). The present results, however, also imply that the predictive power of control response rate in different parts of fixed intervals is limited to those cases in which averages are taken over several repetitions of the interval. The interval-by-interval analyses of response rate showed that the average rates, especially for the middle parts of the intervals, did not represent the actual performance in those parts of the interval. In the middle parts of the intervals, the distributions of response rates from individual intervals were strongly bimodal, and not well characterized by an arithmetic average. An analysis in terms of probability of response rate greater than zero in a specific portion of the interval resulted in relationships between performances under control and drug conditions that were as regular as those obtained for average rate.

The present experiments involved a finer analysis of response rates in tenths of fixed intervals than that provided by taking average rates in each tenth. When a more detailed analysis results in a loss of orderly relationships in exchange for a more complete description, then it is possible to criticize legitimately the use of a fine-grain analysis on the grounds that predictive order has been lost. The present analysis resulted in a more complete description *without* the loss of predictive power, and, thus is not subject to criticism on a "can't-see-the-forest-for-the-trees" basis.

It has been argued that probability of responding and response rate are related (*e.g.*, Skinner, 1950), and the present results demonstrate clearly that the average rate and probability of responding were strongly related within tenths of fixed intervals, and, thus the two measures might be used interchangeably. Probability of responding is to be preferred,

however, for at least two reasons. First, likelihood of responding at all was more descriptive of the interval-by-interval performance. As the analysis of local rates within intervals showed, some tenths of the intervals were characterized by average rates that described not a single instance of the actual control performance. Second, several experiments have shown that the period of pausing, and the nature of the responding during time after the pause in fixed-interval schedules are controlled by different variables (Elsmore, 1971; Killeen, 1969; Shull, 1970*a*,*b*, 1971; Shull, Guilkey, and Witty, 1972). The period of pausing is probably controlled by either the time between reinforcements or by the delay between the response that ends the pause and reinforcement (Schneider, 1969; Sherman, 1959; Shull, 1970*a*,*b*, 1971; Schneider and Neuringer, 1972), whereas the nature of responding after the pause seems to be a function of the contingencies at the moment of reinforcement (Elsmore, 1971; Killeen, 1969; Shull, 1970*b*). Use of an average rate to characterize performance in tenths of fixed intervals, then, not only results in using an average to describe a bimodal distribution, but also results in aggregating two dependent variables that are controlled by different independent variables. These facts lead to serious questions about the appropriateness of using local rates in fixed-interval schedules to examine "rate-dependent" effects of drugs. Some of the rates used as predictors are means from bimodal distributions, and *"the occurrence of even a few very high or very low cases can seriously distort the impression of the distribution given by the mean. . . ."* (Hays, 1963, p. 175, italics in original). Thus, even if there were considerable acceleration in individual fixed intervals, as long as the starting time varied from interval to interval, mean local rates would be heavily influenced by the number of occurrences of a zero rate in a particular segment. In addition, the predictive efficacies of the local rates are confounded because they occur at different times from reinforcement. The "rate-dependency hypothesis" needs to be examined using procedures that produce a variety of rates that are unambiguously rates.

Separating fixed-interval performance into two parts, a period of pausing and a period of responding, yielded information not to be found when the intervals were divided into tenths and average rates accumulated. For example, the present analysis allowed examination of the effects of *d*-amphetamine on the acceleration that occurs during the period of responding in each fixed interval. A traditional measure of acceleration in fixed intervals, the Mathematical Index of Curvature (Fry *et al.*, 1960), was reduced substantially by most doses of *d*-amphetamine, yet the likelihood that responding was accelerated over the period of responding was not changed much by most doses of the drug.

The analyses performed here are directly related to the "two-state" hypothesis of performance under fixed-interval schedules (Schneider, 1969). According to this hypothesis, performance in individual fixed intervals can be characterized by two response rates, a very low, or zero, rate followed by an abrupt transition to a relatively high, constant rate until reinforcement occurs. The high correlation between the average rate in a tenth and the likelihood of responding in that tenth (*i.e.*, the likelihood of being in the "high-rate state") provides strong support for a "two-state" theory. Figures 13 and 14 and Table 2, however, strongly suggest that the rate of responding in the "high-rate state" in fixed intervals is, in fact, accelerated. An amended version of the "two-state" hypothesis that is more in keeping with the present results is that performance under fixed intervals by pigeons can be characterized by two states, a period of very low or zero rate followed by a period of slightly, but reliably, positively accelerated responding. The word "slightly" is used because, as shown in Table 3, the positive acceleration of rate that occurs during the period of responding accounts for less than 10% of the variance in the average scallop.

The present results, then, can be interpreted as supporting a modified two-state hypothesis about pigeons' responding under fixed-interval schedules of reinforcement. The generality of these findings to other species, and to other setting conditions, needs to be examined.

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