

*WITHIN-SESSION RESPONSE RATES WHEN REINFORCEMENT
RATE IS CHANGED WITHIN EACH SESSION*

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Three pigeons pecked keys and 5 rats pressed levers for food delivered on variable-interval schedules. During baseline conditions, subjects responded on a variable-interval 40-s schedule throughout the session. During experimental conditions, the programmed rate of reinforcement changed every 10 min in the 50-min sessions. When rats served as subjects, Herrnstein's (1970) hyperbolic equation provided a good description of the relation between rate of responding during a 10-min interval and the rate of reinforcement obtained during that interval. Responding, measured over 10-min blocks, was also approximately equally sensitive to changes in the programmed rate of reinforcement at all times in the session. Herrnstein's equation provided a poorer description of the changes in responding when pigeons served as subjects. Differences in experimental experience or differences in the absolute rates at which subjects responded may have contributed to the differences in results for these different species.

Key words: variable-interval schedule, within-session patterns of responding, Herrnstein's equation, matching law, key peck, lever press, pigeons, rats

Herrnstein (1970) proposed that a hyperbolic equation describes the relation between rate of responding (P) and rate of reinforcement (R) when subjects respond on simple schedules of reinforcement.

$$P = \frac{kR}{R + R_0} \quad (1)$$

The free parameters, k and R_0 , represent the subject's asymptotic level of responding and the reinforcers obtained from unprogrammed sources, respectively. Although this equation has been criticized (e.g., Dougan & McSweeney, 1985; McDowell & Wood, 1984), it has described the data well in many cases when subjects' responses are reinforced according to variable-interval (VI) schedules. For example, de Villiers (1977) fit Equation 1 to the rates of responding for each of 6 pigeons in a study by Catania and Reynolds (1968). The equation accounted for an average of 88.7% of the variance in the data (range, 76.7% to 99.8%). Equation 1 has also helped to answer some applied questions. For example, Heyman and his colleagues used changes in the two free parameters to separate the motoric (k) and hedonic (R_0) effects of a variety of drugs (e.g., Heyman, 1983).

Two methods have been used to test the accuracy of Equation 1. In the across-sessions procedure, different rates of reinforcement are presented in different experimental conditions. Equation 1 is fit to the average rate of responding emitted and the average rate of reinforcement obtained during the entire session in each experimental condition (e.g., Dougan & McSweeney, 1985). During the within-session procedure, different rates of reinforcement are presented at different times in single experimental sessions. Equation 1 is fit to the rate of responding emitted and the rate of reinforcement obtained at different times within the experimental session (e.g., Heyman, 1983).

The across-sessions method of testing Equation 1 has been challenged recently by the finding that large and systematic changes in response rates may occur within sessions even when reinforcement is held constant within the session (e.g., McSweeney, Hatfield, & Allen, 1990). Although these within-session changes are often studied when subjects respond on multiple VI VI schedules, they have also been reported for the single VI schedules to which Equation 1 is usually applied (McSweeney, Weatherly, & Swindell, in press). The phenomenon of systematic within-session changes in response rates calls into question the use of the across-sessions method, because these changes are often accompanied by systematic changes in both the fit and the

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parameters of Equation 1 within sessions (e.g., McSweeney, 1992; McSweeney, Weatherly, & Swindell, 1995).

The effect of within-session changes in response rates on the within-session method of fitting Equation 1 is not known. Arguments can be made on both sides of this issue. On the one hand, the within-session method uses measures of behavior that are averaged over small units of time (e.g., 10 min). Both the early-session increases and the late-session decreases in responding often occupy longer periods of time (e.g., 20 or 40 min, McSweeney *et al.*, 1990). As a result, the changes in response rates over the short time periods used in the within-session method might not be large enough to distort the results obtained with this method. Changes in the rate of reinforcement within sessions might also exert such powerful control over behavior that any changes in the rate of responding would be determined primarily by the effect of the rate of reinforcement and only minimally by within-session changes in responding that originate from other sources. On the other hand, within-session changes in responding might confound the results when the within-session procedure is used. If different rates of reinforcement are presented at times in the session that ordinarily control different rates of responding, then effect of rate of reinforcement might be confounded by these within-session changes in response rates, distorting the measured fit and the values of the parameters of Equation 1.

The question of whether within-session changes in responding confound the results of the within-session method can be answered by presenting programmed rates of reinforcement in different orders in different experimental conditions. Presenting rates of reinforcement in different orders should yield different estimates of the k and R_0 parameters and percentage of the variance accounted for by Equation 1 if within-session changes in responding confound the within-session method of fitting Equation 1. Presenting rates in different orders should yield similar estimates of the parameters and fit of Equation 1 if within-session changes do not confound the within-session method. A specific example may clarify this approach. Suppose that responding increases to a peak and then decreases within the session when rate of re-

inforcement is held constant within the session (e.g., McSweeney *et al.*, 1990). The size of the k parameter (the asymptotic rate of responding) might be overestimated when the programmed rate of reinforcement increases and then decreases within the session. The high rates of responding that occur towards the middle of the session when rate of reinforcement is constant throughout the session might add to the effect of the high rate of reinforcement presented towards the middle of the session, leading to a high estimate of the value of k . In contrast, the size of k might be underestimated when rates of reinforcement decrease and then increase within the session. The low rates of responding that occur at the beginning and end of the session might lessen the effect of the high rates of reinforcement presented at those times, leading to an underestimate of the value of k (see Belke & Heyman, 1994, for a similar argument).

The present experiment examined whether within-session changes in responding confound the results when the within-session procedure is used to fit Equation 1. During baseline conditions, subjects responded on a VI 40-s schedule of food delivery throughout the session. During experimental conditions, the programmed rates of reinforcement (i.e., the VI schedule value) changed every 10 min during the 50-min sessions. The order of schedule presentation differed in different experimental conditions. If within-session changes in responding confound the results, then the fit and parameters of Equation 1 should differ for different orders of schedule presentation. If within-session changes do not confound the results, then the fit and parameters should not differ for the different experimental conditions.

METHOD

Subjects

The subjects were 5 experimentally naive male rats derived from Sprague-Dawley stock and 3 experimentally experienced homing pigeons. A 4th pigeon began the experiment but died before completion. Its data have been excluded from analysis. The rats were approximately 120 days old at the start of the experiment. The pigeons had responded on

a variety of operant conditioning procedures before the start of the experiment. All subjects were maintained at approximately 85% of their free-feeding weights by postsession feedings given when all subjects had completed their daily sessions. The 85% weights of the individual rats ranged from 330 to 385 g; the 85% weights of the individual pigeons ranged from 320 to 380 g. The 85% weights of the rats were determined by maintaining the subjects on free food for 1 week before the experiment began. The weights of the pigeons had been determined prior to previous experiments. They were not redetermined before this study.

Apparatus

All rats responded in the same two-lever chamber, constructed in the laboratory, measuring 21.5 cm by 20.5 cm by 28 cm. A hole (5.5 cm diameter) that allowed access to the 45-mg Noyes pellets was centered in the logic panel, 1.5 cm above the floor. The two levers, which required a force of approximately 0.30 N to operate, were 5 cm wide and extended 2.5 cm into the chamber. The levers were located 1.5 cm from one side of the apparatus and 7.5 cm above the floor. A white light (2 cm diameter) was centered 5 cm above each of the levers. A green light (2 cm diameter), which served as a houselight, was centered in the logic panel, 2.5 cm below the ceiling. A door that allowed access to a running wheel was on the left wall of the chamber; rats were not allowed access to the wheel during this experiment.

All pigeons responded in the same three-key experimental enclosure, constructed in the laboratory, measuring 32.5 cm by 30.5 cm by 35.5 cm. Three response keys (2.5 cm diameter) were located 23.5 cm above the floor and 7.5 cm apart. Only the left key, located 6.5 cm from the left wall, was used. It required a force of approximately 0.25 N to operate. An opening (6.5 cm by 4 cm, 9 cm below the key) allowed access to a food magazine that contained mixed grain.

The experimental chambers were housed in sound-attenuating chambers. Ventilating fans masked noises from outside the chambers. Experimental events were controlled by a SYM microcomputer, programmed in assembly language, located in another room.

Table 1

The schedules of reinforcement provided in each 50-min session in successive conditions.

Condition	Schedules
Baseline	VI 40
Decrease (DEC)	VI 15, VI 30, VI 60, VI 120, VI 240
Increase (INC)	VI 240, VI 120, VI 60, VI 30, VI 15
INC-DEC	VI 240, VI 30, VI 15, VI 60, VI 120
DEC-INC	VI 15, VI 120, VI 240, VI 60, VI 30
Baseline	VI 40

Note. Schedule values were changed every 10 min except during the baseline conditions. All schedule values are in seconds.

Procedure

The rats were trained to press the left lever using the method of successive approximations. They were then placed on a continuous reinforcement procedure for 200 responses. After that, the ratio of responses to reinforcement was increased according to the performance of individual subjects until subjects responded at a rapid rate. Lever pressing then produced food pellets on a VI 40-s schedule of reinforcement, with intervals derived according to a 25-interval Fleshler and Hoffman (1962) series. The houselight and the light above the left lever were illuminated throughout the session. Sessions were 50 min long and were conducted daily, five to six times per week, from approximately 11:00 a.m. to 4:00 p.m. Sessions were conducted successively, with each subject responding at approximately the same time of day during each session.

Rats responded under the following conditions in the following order: baseline, decrease (DEC), increase (INC), increase-decrease (INC-DEC), decrease-increase (DEC-INC), and return to baseline. During the baseline conditions, reinforcers were available on a VI 40-s schedule of reinforcement for the entire 50-min session. In each of the other conditions, the programmed schedule of reinforcement changed every 10 min. Table 1 lists the schedules that were presented during successive 10-min intervals in the order in which they were available in each condition. A VI 40-s schedule was chosen as the baseline because it presents approximately the same average programmed rate of reinforcement (approximately 90 reinforcers per hour) as that presented by the series of

schedules offered in the other conditions. Each condition was presented for 30 sessions.

The pigeons had pecked keys in previous experiments. Therefore, key pecking was placed directly on the baseline VI 40-s schedule. Reinforcement was 5-s access to mixed grain. The timer that timed the session and the 10-min intervals stopped during reinforcement. Experimental sessions were conducted from approximately 10:00 a.m. to 2:00 p.m. All other procedural details were the same as those for rats.

RESULTS

Figures 1 and 2 present the individual-subject mean rates of responding (responses per minute), for rats and pigeons, respectively, during successive 5-min intervals in the last five sessions of each experimental condition. These data suggest that response rates changed within sessions during the two baseline conditions, although these changes were not always large or consistent in form across the two baseline conditions. To determine whether the changes were statistically significant, a two-way (baseline by 5-min interval) within-subject analysis of variance (ANOVA) was applied to the baseline rates of responding by individual subjects during the last five sessions of the two baseline conditions. Results of these ANOVAs appear in Table 2. Here and throughout this paper, results will be considered to be significant when $p < .05$.

Table 2 shows that baseline rates of responding changed within sessions (statistically significant main effect of 5-min interval) for all subjects except Rat 704. One-way (5-min interval) within-subject ANOVAs applied to the rates of responding by Rat 704 during the last five sessions for which each baseline was available showed that responding changed significantly within sessions during the second, $F(9, 36) = 3.35$, but not during the first, $F(9, 36) = 1.23$, baseline condition.

Table 2 also shows that the differences in average rates of responding for the entire session during the two baselines were statistically significant for all subjects except Rat 702 (significant main effect of baseline). The within-session patterns of responding differed significantly between the baselines (statistically

significant interaction term) for all pigeons and for 2 rats (701 and 704).

Figures 1 and 2 show that changes in the programmed rate of reinforcement within the session changed the pattern of responding within the session. That is, within-session patterns of responding differed across different experimental conditions. Figure 3 clarifies these changes. It presents the rate of responding (responses per minute) during each 10-min interval of each experimental condition (i.e., excluding baseline conditions) as a function of the rate of reinforcement (reinforcers per hour) obtained during that 10-min interval.

Table 3 presents the k and R_0 parameters of Equation 1 and the corrected percentage of the variance in the data accounted for by Equation 1 for each subject and for the mean of all subjects responding in each experimental condition. Equation 1 was fit to the data using the nonlinear curve-fitting procedure in SYSTAT. This program uses an iterative procedure to determine the least squares fit to the data. The maximum number of iterations was 20.

Equation 1 usually provided a good description of the data when rats served as subjects. The equation accounted for a substantial percentage of the variance in the data (>80%) for all rats except Rat 701 during the INC condition and Rat 705 during the INC-DEC condition. Neither the fit nor the size of the k and R_0 parameters varied systematically with the order of schedule presentation when rats served. The size of R_0 was somewhat smaller for the mean of all subjects responding during INC than during the other conditions, but this difference did not appear consistently for individual subjects (see, e.g., Rats 702 and 704).

Equation 1 did not describe the data as well when pigeons served as subjects. The equation provided a good description of some data (e.g., the DEC condition), but it described the data poorly for Bird 5706 and for all subjects responding during the DEC-INC condition. Changes in the order of schedule presentation also produced some changes in the fit and parameters of Equation 1. Equation 1 described the data less well in the DEC-INC condition than in the other conditions. The size of R_0 was also somewhat larger for

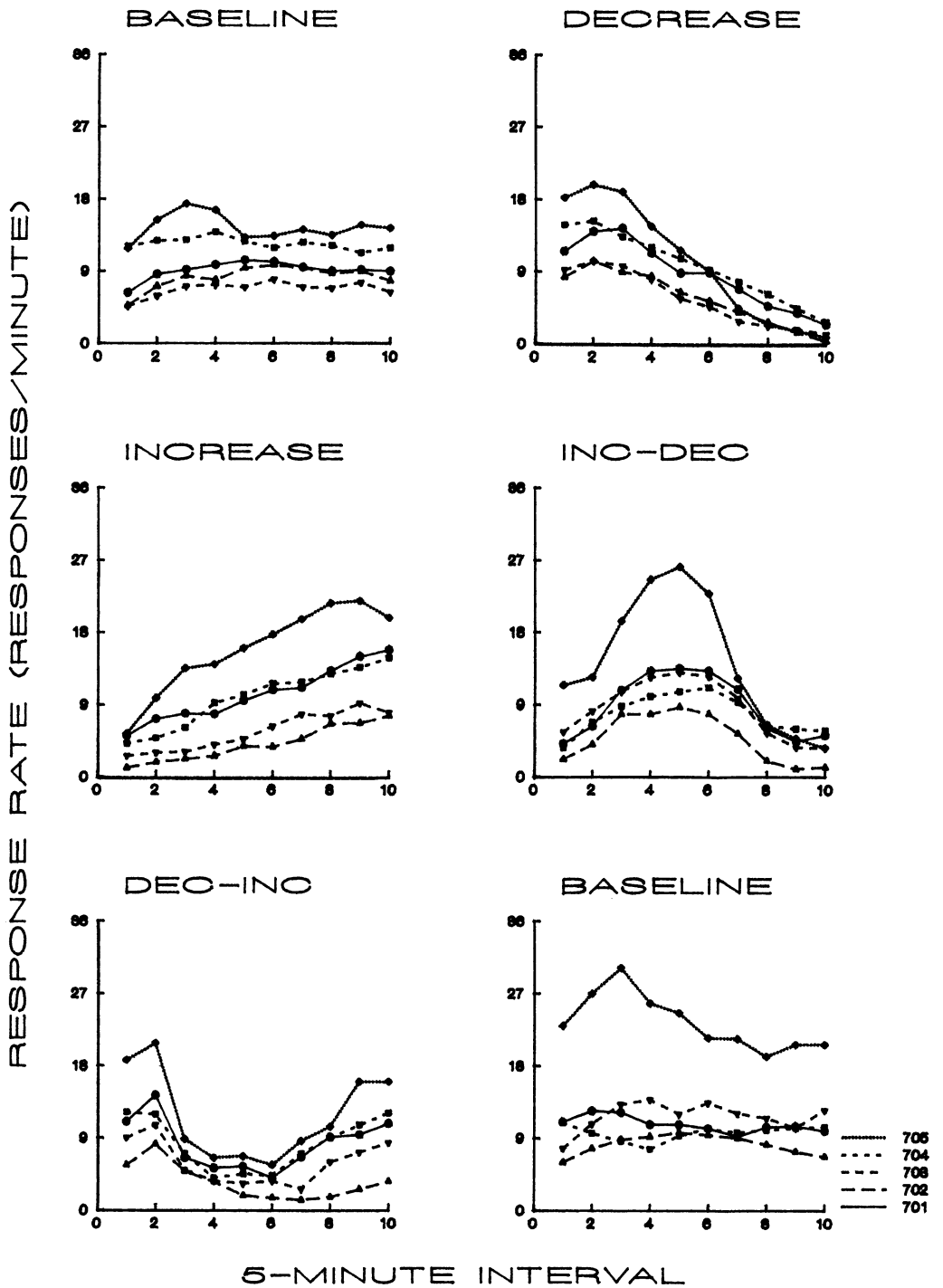


Fig. 1. Rate of responding (lever presses per minute) by rats during successive 5-min intervals in the session. Each graph presents the results for a different experimental condition, as defined in Table 1. Each function describes the results for an individual rat. Each point is a mean, calculated over the last five sessions of each condition.

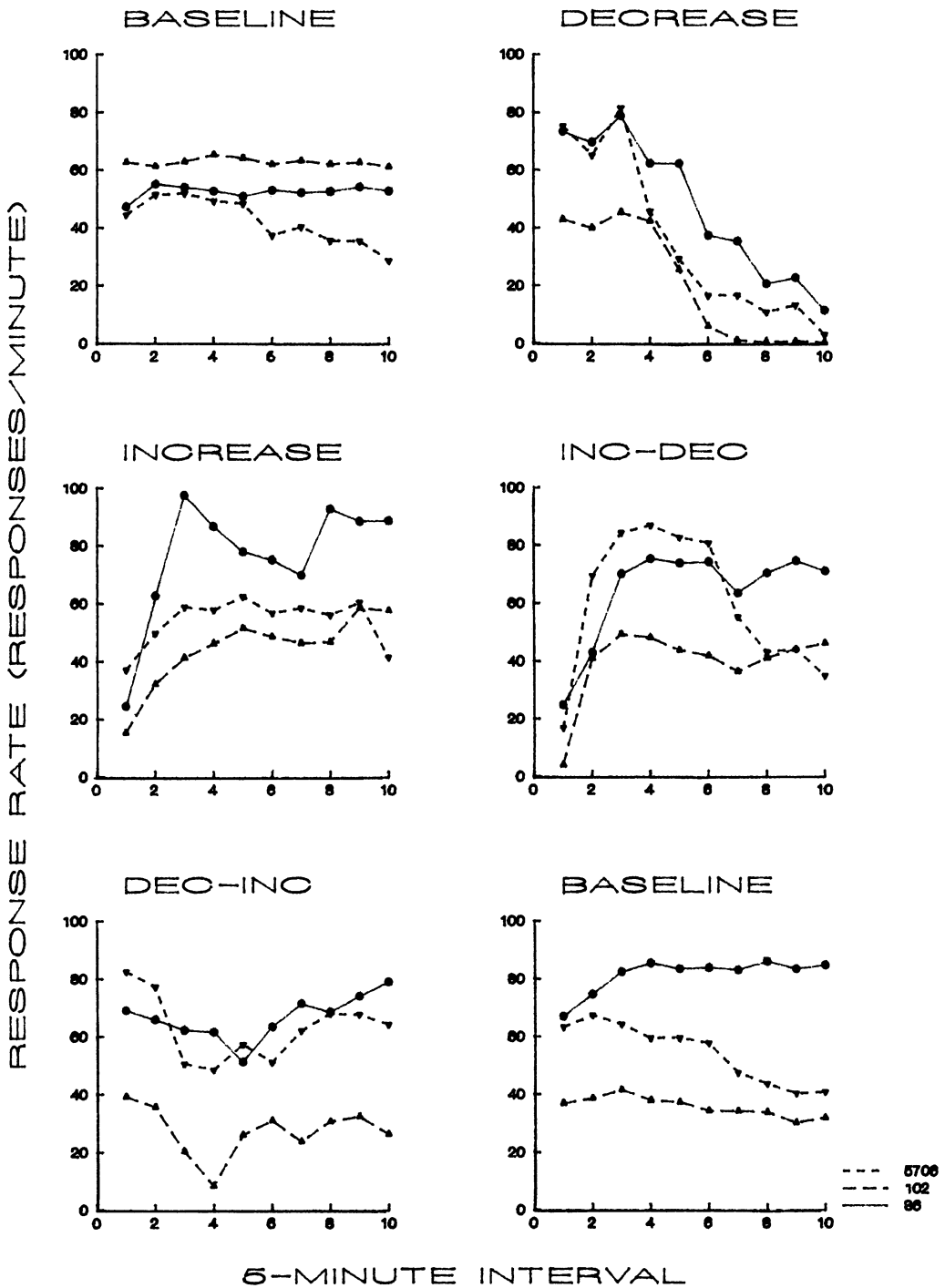


Fig. 2. Rates of responding (key pecks per minute) by pigeons during successive 5-min intervals in the session. Each graph presents the results for a different experimental condition, as defined in Table 1. Each function describes the results for an individual pigeon. Each point is a mean, calculated over the last five sessions of each condition.

Table 2

Results of two-way (baseline by 5-min interval) within-subject analyses of variance applied to the rates of responding by individual subjects during the last five sessions for which each baseline was available.

Source	Rats			Pigeons		
	Subject	<i>df</i>	<i>F</i>	Subject	<i>df</i>	<i>F</i>
Baseline (B)	701	1, 4	14.14*	36	1, 4	42.90**
5-min interval (T)		9, 36	3.22**		9, 36	5.45***
B × T		9, 36	6.00***		9, 36	3.40**
Baseline	702	1, 4	0.01	102	1, 4	11.77*
5-min interval		9, 36	14.69***		9, 36	16.56***
B × T		9, 36	1.35		9, 36	5.09***
Baseline	703	1, 4	19.16*	5706	1, 4	12.85*
5-min interval		9, 36	2.77*		9, 36	40.59***
B × T		9, 36	0.78		9, 36	7.03***
Baseline	704	1, 4	23.10**			
5-min interval		9, 36	0.35			
B × T		9, 36	3.45**			
Baseline	705	1, 4	11.23*			
5-min interval		9, 36	3.24**			
B × T		9, 36	1.72			

* $p < .05$.

** $p < .01$.

*** $p < .001$.

each pigeon responding during the DEC condition than during the other conditions.

DISCUSSION

Rates of responding usually changed significantly within the session during the baseline conditions. The only exception occurred for Rat 704 responding during the first baseline. However, these within-session changes in responding were not as large or as obviously bitonic as those reported in some past studies (e.g., McSweeney et al., 1990). For example, when the rate of responding during the highest 5-min interval was divided by the rate during the lowest 5-min interval, the ratios were 1.41 and 1.25 for the first and second baselines for rats and 1.19 and 1.22 for the first and second baselines for pigeons. In contrast, rates of responding changed by a ratio of approximately 4.5 when rats pressed keys for sweetened condensed milk delivered by multiple VI 60-s VI 60-s schedules (McSweeney et al., 1990).

The reasons for the relatively small within-session changes in responding during the present baselines are not known. However, the use of a single VI schedule may have con-

tributed. A single VI schedule was used here so that Equation 1 could be applied to the data. In contrast, many past studies of within-session changes in responding have used multiple VI VI schedules. Some evidence suggests that within-session changes in responding may differ when subjects respond on VI and multiple VI VI schedules. McSweeney et al. (in press) reported that responding primarily increased within sessions when rats pressed levers for Noyes pellets delivered by VI 15-s and VI 30-s schedules. In contrast, responding primarily decreased (multiple VI 15 s VI 15 s) or increased and then decreased (multiple VI 30 s VI 30 s) within the session when rats responded on comparable multiple schedules (McSweeney, 1992). Within-session changes in responding were also relatively small when subjects responded on VI schedules. Although McSweeney et al. (in press) did not examine responding during a VI 40-s schedule comparable to the one used here, they did examine responding during VI 60-s schedules. Responding changed by a ratio of 1.47 for rats and by a ratio of 2.30 for pigeons on these schedules. Those within-session changes are somewhat larger than those re-

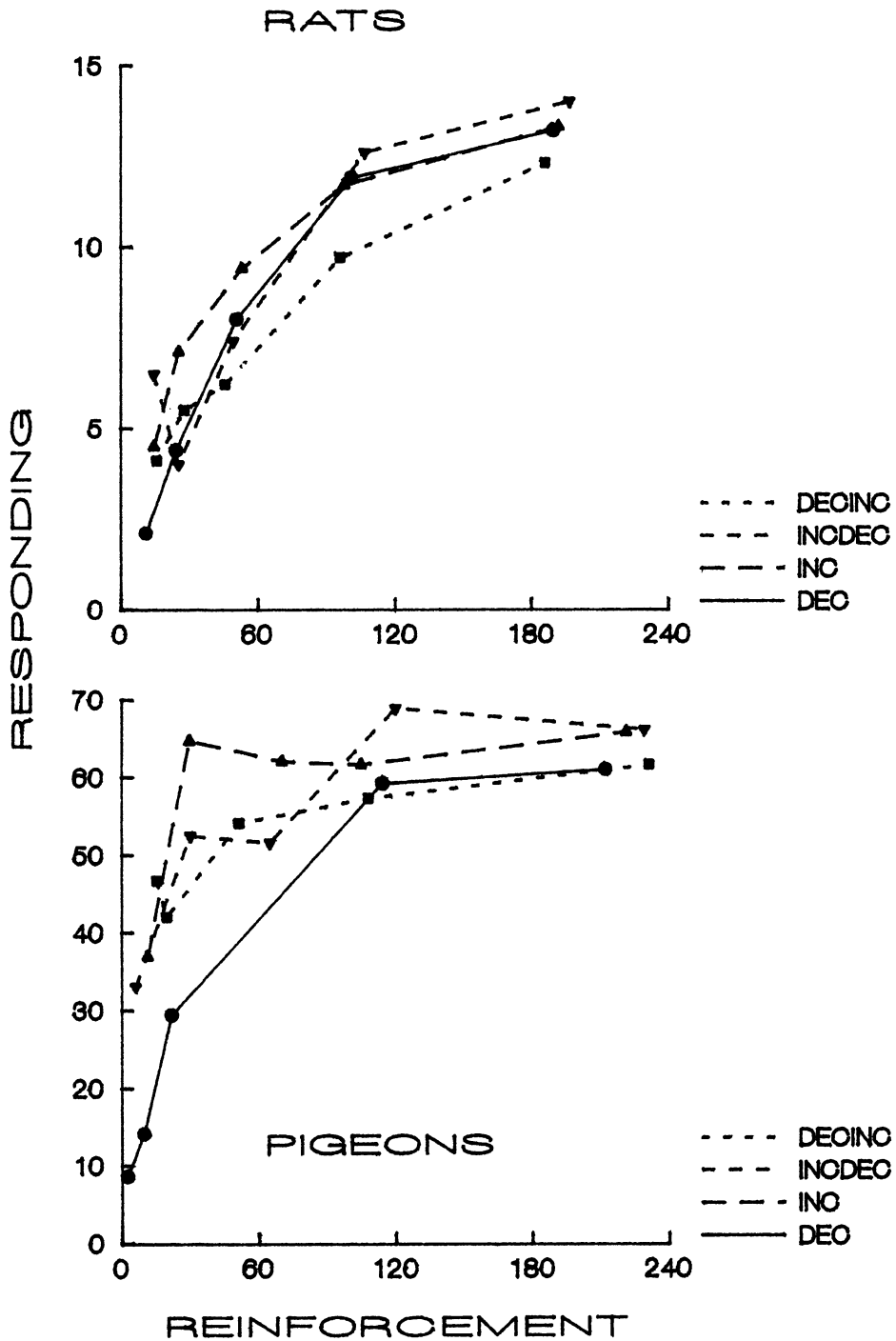


Fig. 3. Rates of responding (responses per minute) as a function of obtained rates of reinforcement (reinforcers per hour) in 10-min periods of each experimental condition when rats (top axes) and pigeons (bottom axes) served as subjects. Each point is a mean of the last five sessions of each condition averaged across all subjects. The experimental conditions are given in Table 1.

Table 3

The k and R_0 parameters of Herrnstein's hyperbolic equation and the corrected percentage of the variance in the data accounted for by this equation for each subject responding during each experimental condition.

Subject		Experimental condition			
		DEC	INC	INC-DEC	DEC-INC
Rat 701	k	16.9	12.3	16.3	14.7
	R_0	47.6	5.4	40.4	42.2
	r^2	97.2	9.0	91.8	97.3
Rat 702	k	13.2	10.4	14.0	11.2
	R_0	63.1	70.1	104.6	103.8
	r^2	96.0	99.6	86.8	81.3
Rat 703	k	16.6	10.9	14.9	13.1
	R_0	111.0	42.3	33.6	66.6
	r^2	98.4	97.1	84.1	94.2
Rat 704	k	18.7	17.8	12.0	14.4
	R_0	48.8	45.8	26.7	34.3
	r^2	99.7	97.4	94.0	99.0
Rat 705	k	28.4	23.7	40.9	24.7
	R_0	88.5	20.1	135.7	57.3
	r^2	97.2	94.6	64.5	93.7
M	k	18.7	15.6	18.1	15.6
	R_0	69.5	33.0	56.0	56.1
	r^2	98.6	99.6	83.1	97.0
Bird 36	k	80.4	90.7	77.4	74.7
	R_0	20.9	6.3	6.4	5.4
	r^2	93.2	79.0	90.6	59.6
Bird 102	k	48.8	59.3	49.9	34.5
	R_0	23.7	14.8	5.5	8.5
	r^2	99.1	86.3	80.9	44.7
Bird 5706	k	95.6	58.1	81.5	72.0
	R_0	66.9	2.9	15.5	4.3
	r^2	98.6	39.9	43.8	54.7
M	k	72.4	69.1	66.3	61.7
	R_0	31.8	7.3	6.9	6.7
	r^2	98.8	79.2	85.5	86.4

Note. The experimental conditions are defined in Table 1.

ported here, but they are smaller than those that are often reported when subjects respond on multiple schedules (e.g., McSweeney et al., 1990).

It is not known why the rate of responding averaged over the session often changed from the first to the second baseline (statistically significant main effects of baseline in Table 2). However, fluctuations in absolute rates of responding are often observed between the presentation of a schedule and its recovery (e.g., Spealman & Gollub, 1974). Large fluctuations in response rates might be expected in the present experiment because four ex-

perimental conditions, which occupied 120 experimental sessions, intervened between the first and second baselines.

Equation 1 provided a good description of the results of each experimental condition for rats (see Figure 3 and Table 3). Neither the fit nor the parameters of the equation changed systematically with changes in experimental condition. As argued earlier, these results imply that the within-session changes in responding that are often observed when rate of reinforcement is held constant within the session did not interfere with the changes in response rates that occur when rate of reinforcement is changed within the session. This, in turn, supports the use of the within-session method to measure Equation 1 when rats serve as subjects.

Finding that the fit and parameters of Equation 1 did not differ when the schedules were presented in different orders for rats indicates that their responding was approximately equally sensitive to reinforcement at all times during the experimental session. If rate of responding had been sensitive to rate of reinforcement early but not later in the session, then the fit of Equation 1 would have been similar for experimental conditions that delivered the same programmed rate of reinforcement early in the session (e.g., the INC and INC-DEC conditions), regardless of the conditions of reinforcement provided later in the session. The fit and parameters for those conditions would have differed from the fit and parameters for conditions that provided a different programmed rate of reinforcement early in the session (the DEC and DEC-INC conditions).

Equation 1 provided a poorer description of the data for pigeons, and the parameters may have changed with changes in the order of schedule presentation. This suggests that within-session changes in response rates may have confounded the effect of changes in the rate of reinforcement within the session. It also suggests that further experiments should be conducted before the within-session method is used to fit Equation 1 when pigeons serve as subjects.

The reasons for the differences between the results for pigeons and rats are not known. However, several procedural differences may have contributed. For example, the pigeons were experimentally experi-

enced; the rats were naive. The pigeons also responded more rapidly than the rats did. Therefore, a ceiling effect may have confounded the results for pigeons. Future experiments should systematically examine the effect of these variables.

The use of the within-session procedure to examine Equation 1 should be verified in further studies. The present finding that within-session changes in responding did not distort the fit of Equation 1 for rats is relatively convincing because within-session changes in responding, although usually small, were observed during the baseline conditions. This rules out one artifactual explanation for the present results. It cannot be argued that within-session changes in responding did not distort the fit of Equation 1 because the conditions used in the present experiment did not produce within-session changes in responding. However, the present results would be more convincing if within-session changes in reinforcement rate had been shown to overcome larger within-session changes in responding. This could be tested in an experiment that provided higher rates of reinforcement during the baseline and experimental conditions, because larger within-session changes in responding often occur during schedules that provide higher rates of reinforcement (e.g., McSweeney, 1992).

The within-session procedure may prove to be quite useful for testing Equation 1 if its use is justified by further experiments. The within-session procedure has some advantages over the alternative across-sessions procedure. To begin with, it saves time. A single session provides data that must be collected over several sessions when the across-sessions procedure is used. The within-session procedure may also provide a relatively accurate measure of the effect of the independent variable. As noted earlier, large shifts in baseline response rates may occur when several sessions are conducted (e.g., Spealman & Gollub, 1974). When different values of the independent variable are presented in different blocks of sessions, shifts in baseline rates may contribute to variability in the data, obscuring the effect of the independent variable. By contrast, when different values of the independent variable are presented in the

same session, as they are in the within-session procedure, longer term baseline shifts cannot add variability, and a less confounded measure of the effect of the independent variable should result. These practical advantages of the within-session procedure suggest that it deserves further study.

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