DURATION AND RATE OF REINFORCEMENT AS DETERMINANTS OF CONCURRENT RESPONDING¹

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The duration and frequency of food presentation were varied in concurrent variable-interval variable-interval schedules of reinforcement. In the first experiment, in which pigeons were exposed to a succession of eight different schedules, neither relative duration nor relative frequency of reinforcement had as great an effect on response distribution as they have when they are manipulated separately. These results supported those previously reported by Todorov (1973) and Schneider (1973). In a second experiment, each of seven pigeons was exposed to only one concurrent schedule in which the frequency and/or duration of reinforcement differed on the two keys. Under these conditions, each pigeon's relative rate of response closely matched the relative total access to food that each schedule provided. This result suggests that previous failures to obtain matching may be due to factors such as an insufficient length of exposure to each schedule or to the pigeons' repeated exposure to different concurrent schedules.

Key words: concurrent schedules, amount of reinforcement, rate of reinforcement, choice, pigeons

Todorov (1973) and Schneider (1973) reported the effects on concurrent-schedule performance of variations in both the rate and amount of reinforcement. Their experiments were the outgrowth of earlier research in which these variables were manipulated separately. Herrnstein (1961) showed that relative rate of response was a linear function of relative rate of reinforcement in concurrent variable-interval (VI) schedules, expressed in the now-familiar "matching" equation:

$$\frac{R_1}{R_1 + R_2} = \frac{r_1}{r_1 + r_2}, \quad (1)$$

where R represents response rate, r represents reinforcement rate, and the subscripts denote the two response keys on which the pigeon pecked.

A similar relation was reported when, with the rate of reinforcement held constant, the amount of reinforcement was varied. Catania (1963) scheduled different magazine durations (d) for two concurrent operants while holding

the number of reinforcements equal. For three different combinations of magazine duration, the matching equation obtained. That is,

$$\frac{R_1}{R_1 + R_2} = \frac{d_1}{d_1 + d_2}. \quad (2)$$

Equations 1 and 2 indicate that rate and duration of reinforcement have equivalent behavioral effects. Furthermore, since there of course can be no rate of reinforcement without a reinforcement duration, nor a duration without a rate, these variables would appear to combine multiplicatively in controlling relative response rates under concurrent VI VI schedules. First suggested by Premack (1965) and subsequently, in somewhat altered form, by Baum and Rachlin (1969), this relation can be expressed as:

$$\frac{R_1}{R_1 + R_2} = \frac{r_1 d_1}{r_1 d_1 + r_2 d_2}. \quad (3)$$

That is, relative response rate matches the relative access to reinforcement provided by the concurrent VI schedules.

Given the validity of Equations 1 and 2, Equation 3 would appear to be logically imperative. Hence, it is surprising that neither Todorov nor Schneider obtained results that conformed to its prediction. Both trained pigeons under concurrent VI VI schedules of reinforcement and then varied the relative fre-

¹Experiment I was supported by USPHS Grant No. MH-01604. Portions of the data were presented at the meeting of the American Psychological Association, 1976. The authors thank P. Bobko and K. Norman for statistical advice. Reprints may be obtained from L. R. Gollub, Department of Psychology, University of Maryland, College Park, Maryland 20742. European readers can obtain reprints from J. V. Keller, Dept. of Psychology, Tilburg University, Tilburg, The Netherlands.

quency and amount of reinforcement available under each VI schedule. Both found that variations in the product of reinforcement frequency and amount had less effect on relative response rate than predicted by Equation 3. In both studies, reinforcement rate appeared to determine relative response rate more powerfully than did amount of reinforcement. The present experiments examined procedural variables that may account for these findings.

EXPERIMENT I

Although logically straightforward, the experiments of Todorov (1973) and Schneider (1973) were procedurally complex. In Todorov's study, for example, three different pairs of VI schedules, each associated with a different combination of key colors, were presented successively within a single session. Throughout the experiment, a given key color was always associated with the same rate of VI reinforcement, while the duration of reinforcement associated with that key color varied across conditions. Previous concurrent research usually presented only one pair of schedules for many sessions until behavioral stability was achieved. Furthermore, the consistent coupling of reinforcement rate and key color throughout Todorov's study may account for the greater effect of this variable on relative response rate than reinforcement duration, whose correspondence with key color varied across conditions.

Todorov used Findley's (1958) method of concurrent scheduling, wherein the pigeon changes the stimuli and their associated schedules on one key by pecking a second "changeover" key. Typically, changeover responses initiate a brief period in which reinforcement is not available. This period, termed a changeover delay (COD), is typically not correlated with a specific stimulus and pecks on the main key during this period occur at a high rate (Silberberg and Fantino, 1970). In Todorov's experiment, however, changeover responses produced a brief timeout, during which the chamber lights and keylights were turned out and the scheduling and recording devices stopped. The effects of a changeover-produced timeout have been investigated only twice previously (Silberberg and Fantino, 1970; Todorov, 1971). In these studies, the timeout, like the COD (Herrnstein, 1961; Shull and Pliskoff,

1967), reduced the frequency of alternation between schedules. However, the timeout procedure appeared to produce greater differences in relative response rates than the more common COD procedure.

Schneider used Herrnstein's (1961) method of concurrent scheduling in which both concurrent operants are available simultaneously (the COD being initiated by a switch from one key to another). However, instead of being scheduled independently, as is usually the case, successive VI reinforcers were allotted to one key or the other in a predetermined irregular sequence. This method equalizes the scheduled and obtained reinforcements for each response alternative, but the schedules are not independent. Prolonged responding on the preferred key may be reduced by the contingency that prevents reinforcements on that key from being delivered until previously scheduled reinforcements on the nonpreferred key have been obtained. Hence, such a schedule may generate more equal responding than would independent VI schedules. This feature of Schneider's study might account for the failure to obtain matching to either rate or amount of reinforcement. However, in previous studies with a procedure like this, relative rate of reinforcement matched relative rate of response (Heyman, 1976; Shimp, 1971; Stubbs and Pliskoff, 1969). The only study using this procedure to study reinforcement duration (Fantino, Squires, Delbrück, and Peterson, 1972) produced the same degree of "undermatching" as independent VI schedules, so long as the latter schedule provided an equivalent rate of obtained reinforcement.

Schneider's procedure was also somewhat unusual in using food pellets rather than a period of access to grain as the reinforcer for the pigeons. Delivering a series of spaced food pellets controlled not only duration of reinforcement but also amount of food ingested, and perhaps the rate of ingestion as well. Previous studies typically varied amount of reinforcement by varying the duration of feeder presentation (*cf.* Brownstein, 1971; Catania, 1963). In Schneider's method, pellets later in the sequence may have a weaker reinforcing effect than those temporally closer to the reinforced response. Thus, each pellet may make a smaller contribution than the one before it, and reinforcer efficacy may be a nonlinear function of pellet number. Alternatively, in the

standard procedure as well as in Schneider's, different portions of the feeder cycle may not contribute equally to the reinforcement of responses. The issue remains open, and there is no *a priori* reason that variations in pellet number and feeder duration should have equivalent behavioral effects.

Due to the uncertain contribution of these variations in procedure to the findings of Todorov and Schneider, Experiment I re-examined the effect of varied reinforcement rate and duration on concurrent responding, with a procedure more representative of those used previously to study these variables in isolation.

METHOD

Subjects

Three male White Carneaux pigeons were maintained at 80% of their free-feeding weights. All had extensive prior training. In their home cages, the pigeons had free access to water and grit, and their weights were controlled by rationed postsession feedings.

Apparatus

In a two-key Foringer pigeon box, the left and right response keys were lit from behind by white and red lights, respectively, and were spaced 7.0 cm apart, 22.0 cm above the floor. Key pecks of a force greater than 0.15 N activated the recording and scheduling equipment in an adjacent room and produced a click from a relay located behind the response panel, equidistant from the keys. Just inside the aperture of the feeder was a photobeam that bisected the opening in a horizontal plane. Entry of the pigeon's head interrupted this beam and, depending on whether a left- or a right-key peck had produced the reinforcer, activated either of two running-time meters, which cumulated eating time over the session. White noise was continuously broadcast in the experimental room, and the chamber's ventilating fan provided additional masking noise.

Procedure

Two variables were manipulated: the mean interreinforcement interval of the arithmetic VI schedules (10, 20, 30, 40, or 50 reinforcements per hour) and the duration of food presentation (1, 2, 3, 4, or 5 sec) associated with responding on each key. Eight different combinations of duration and rate were studied,

and, for each combination, the sum of the reinforcement rates was maintained at 60 per hour, and similarly, the sum of the two magazine durations was held at 6 sec. A 2-sec COD (Herrnstein, 1961) was in effect throughout the experiment.

Table 1 shows the eight combinations of reinforcement rate and duration. Pigeon 128 was not studied under the first condition, and ill health prevented Pigeon 108 from being used in the last condition. Sessions were conducted daily, and changes in condition were made when a visual inspection of graphs of relative response rates revealed little systematic day-to-day variability.

RESULTS

Table 1 shows the data for each bird averaged over the last five sessions of each condition, and Figure 1 shows relative response rate as a function of relative reinforcement access time. Response proportions from individual sessions differed from the five-session means presented in this figure by no more than 0.04. Reinforcement access time is here defined as the product of obtained rate of reinforcement and duration of feeder presentation. While these data tend to approximate the matching relation (indicated by the dashed diagonal line in each panel of the figure) more closely than do the data of Todorov (1973) or Schneider (1973), a pattern of "undermatching" is apparent in the data of all pigeons. Points in the lower-left quadrant of each panel tend to lie above the diagonal, while in the upper-right quadrant they tend to lie below the diagonal. Thus, variations in the product of reinforcement rate and duration exerted less control over response distribution than is predicted by Equation 3.

In most conditions the proportion of reinforcements actually obtained by the pigeons under each VI schedule differed little from the proportion of reinforcements that these schedules could optimally provide. Hence, a substitution of scheduled reinforcements for obtained reinforcements in the calculation of reinforcement access time has little effect on the data in Figure 1.

Figure 2 shows, over all conditions, the relation between duration of magazine operation and duration of photobeam interruption by the pigeon's head during feeder operation.

Table 1

Summary of experimental conditions and data from Experiment I. The data are means from the last five sessions of each condition. *Eating Time* is the mean duration of head entry to the food magazine. Session duration was 50 min in Condition 1 and 45 min in subsequent conditions. *L*-left, *R*-right.

Sub- ject	Condi- tion	Ses- sions	Sched- uled Rfts per Hour		Rft Duration (sec)		Obtained Rfts per Hour		Eating Time (sec)		Responses per Minute		Change- overs per Minute
			L	R	L	R	L	R	L	R	L	R	
P-108	1	60	30	30	3	3	24	28	2.0	1.9	28.4	33.0	6.7
	2	79	30	30	4	2	29	27	3.0	0.9	55.2	19.6	9.6
	3	32	20	40	3	3	19	38	2.0	2.0	36.4	21.3	6.3
	4	70	10	50	2	4	9	47	0.9	2.9	11.9	33.1	2.4
	5	80	50	10	3	3	45	9	1.9	1.8	48.1	21.9	7.3
	6	29	40	20	2	4	35	19	0.9	2.8	30.9	49.4	7.1
	7	35	40	20	5	1	39	16	3.9	0.0	61.3	13.2	4.3
P-128	2	37	30	30	4	2	29	30	3.3	1.3	57.6	42.9	8.2
	3	32	20	40	3	3	18	39	2.3	2.4	36.7	73.2	6.6
	4	70	10	50	2	4	9	46	1.3	3.2	15.5	68.4	3.3
	5	80	50	10	3	3	47	9	2.1	2.0	84.2	45.3	12.1
	6	29	40	20	2	4	36	19	1.2	2.6	64.9	57.3	10.0
	7	35	40	20	5	1	39	19	3.8	0.5	82.3	50.3	12.1
	8	51	20	40	2	4	20	39	1.2	3.1	41.3	71.3	6.9
P-129	1	52	30	30	3	3	26	30	0.4	0.4	28.8	25.9	5.8
	2	79	30	30	4	2	28	28	1.0	0.6	39.7	32.5	8.1
	3	32	20	40	3	3	19	40	1.1	1.1	29.0	62.6	6.8
	4	70	10	50	2	4	7	44	0.3	0.7	7.0	35.9	2.0
	5	80	50	10	3	3	46	9	0.7	0.7	50.3	21.4	6.5
	6	29	40	20	2	4	35	18	0.3	0.6	30.3	41.3	7.7
	7	35	40	20	5	1	39	16	0.9	0.1	56.5	10.6	2.4
	8	51	20	40	2	4	18	40	0.6	0.9	19.5	51.1	5.0

Pigeon 129 ate in an unusual manner. Instead of keeping its head in the feeder during the reinforcement period, this bird withdrew its head after each brief thrust at the grain. This behavior was less efficient than that of the other birds, in terms of the bird's weight-gain during the session, but it persisted through the experiment. Pigeons 108 and 128 kept their heads in the feeder, and their eating times are approximately linear functions of the duration of feeder operation. At the 1-sec feeder duration, none of the birds was able to eat for more than a small fraction of the period. In fact, there was never a recorded instance of eating by Pigeon 108 at this feeder duration.

Substituting eating duration for feeder duration in the calculation of reinforcement access time would result in a still greater disparity from matching in Figure 1, since this substitution is roughly equivalent to subtracting a constant (1 sec) from both d_1 and d_2 . At the 1-sec feeder duration, calculations based on eating time would predict that virtually all responses would be made on the key associated

with the longer reinforcement duration. The result of the seventh condition, where a 1-sec duration was coupled with a 5-sec duration, is indicated by the data point at the extreme right in each of the functions of Figure 1. After 35 sessions of this condition, all pigeons continued to respond on the key associated with the 1-sec duration, despite the fact that for Pigeons 128 and 129 these responses provided very little grain, and for Pigeon 108 they provided none at all.

It is possible to give different exponents to the reinforcement frequency and duration variables of Equation 3 and thus estimate the degree to which each determined the pigeons' relative response rates. When this was done with the present data, by means of both an iterative computer method like that of Todorov (1973) and the multiple regression method of Schneider (1973), the results were inconsistent across subjects: the reinforcement-rate exponent was less than the duration exponent for Pigeon 108, greater than the duration exponent for Pigeon 128, and

Fig. 1. Relative response rate as a function of relative reinforcement access time for three pigeons separately and for the group as a whole. Each point represents the mean over the last five sessions of a condition. The letter R represents the response rate, r the obtained rate of reinforcement, d the duration of feeder presentation, and subscripts 1 and 2, the left and right response keys, respectively.

for Pigeon 129 the duration exponent was slightly greater. Thus, these results do not agree with Todorov's and Schneider's findings of a consistently greater degree of behavioral control by reinforcement rate than by reinforcement duration. Furthermore, only in the case of Pigeon 108's duration exponent did any exponent approach 1. As Schneider also found, there was a general failure to match

either duration or rate of reinforcement, even in conditions of the experiment where only one or the other of these variables was different on the two keys.

DISCUSSION

Both the present experiment and Schneider's (1973) included several experimental conditions in which only one of the

two variables was not the same. Yet, even the data from these conditions failed to show matching. Thus, there was a failure to confirm not only Equation 3, but also Equation 1, when only the rate of reinforcement differed on the two keys, and Equation 2, when only duration differed.

Fig. 2. The duration of feeder photobeam interruption as a function of the duration of grain availability. Data were averaged across the last five sessions of all conditions.

In accounting for his and Todorov's (1973) finding of weaker control by reinforcement duration, Schneider questioned the basic assumption of Equation 2 that relative response rates match relative reinforcement duration. Catania (1963) obtained an approximate match to three different magazine durations, and Brownstein (1971) also found that the time spent by pigeons in the presence of each of two concurrent schedules of response-independent reinforcement matched relative reinforcement duration. Likewise, using Autor's (1960) concurrent-chains procedure, Ten Eyck (1970) reported a match of relative first-link response rates to relative reinforcement duration in the second links, and Neuringer (1967), who used a variant of this procedure, reported a comparable relation for first-link "choice" responses. But others, such as Walker, Schnelle, and Hurwitz (1970), who used rats and varied the relative duration of access to a sucrose solution, and Fantino *et al.* (1972), who used pigeons and a single combination of reinforcer durations,

reported that reinforcement duration has less effect on relative response rates than predicted by the matching rule. On the basis of these latter findings, Schneider argued that in his and Todorov's studies, the weaker effect of reinforcement duration may be due to the fact that even when manipulated alone, reinforcement duration is a less potent determinant of relative response rate than is the relative rate of reinforcement.

While the literature is not unanimous in its appraisal of the effects of reinforcement duration on concurrent responding, the match of relative response rate to relative reinforcement rate has been repeatedly demonstrated with a wide variety of procedures (including ones which, like Schneider's, have used non-independent VI schedules). Thus, Schneider's failure, and our own, to replicate Equation 1, when only the rate of reinforcement was different, is particularly troublesome. Experiment II, below, investigated a possible source of the apparent attenuation of schedule control evidenced in Experiment I and in the research of Todorov and Schneider.

EXPERIMENT II

In Experiment I, many sessions were conducted under each condition and the procedure was much the same as that of Herrnstein (1961) and Catania (1963). However, the possibility remains that the pigeons' prolonged exposure to a variety of durations and rates of reinforcement attenuates concurrent schedule control. Experiment II was designed as a rough test of this possibility. In most regards, the procedure was the same as that of Experiment I; however, instead of each pigeon being exposed to all conditions, each was exposed to only one condition in which the rate and/or duration of reinforcement was different on the two keys. Hence, there was a greatly reduced possibility of an interaction among schedule conditions.

METHOD

Subjects

Seven male homing pigeons, obtained in the region of Tilburg, The Netherlands, had prior training on single-key schedules and were maintained at 80% of free-feeding weights.

Apparatus

Experimental sessions for the seven pigeons were conducted simultaneously in identical BRS/LVE (model 141-21) two-key pigeon chambers. The left and right keys were illuminated by red and green lights, respectively. A PDP 8/e computer recorded the data and controlled the experiment.

Procedure

All seven pigeons were exposed to the first condition of Experiment I (in which the rates and durations of reinforcement were the same on both keys), but then each bird was exposed to a different condition in which reinforcement rates and/or durations were not equal.

Unlike Experiment I, sessions were terminated after 40 reinforcements, rather than after 45 min, and computer-generated constant-probability VI schedules were used, instead of arithmetic VIs.

RESULTS

Table 2 shows the schedule parameters for each bird and data averaged over the last five sessions of each condition.

Figure 3 shows relative response rate as a function of the relative reinforcement access time. The open circle represents the average relative response rate of all pigeons in the first experimental condition; under equal rein-

forcement rates and durations, all pigeons responded about equally often on the two keys. The remaining data points (solid circles) each represent the behavior of a single pigeon in one of the seven schedule conditions. The response proportions from individual sessions differed by no more than 0.04 from the five-session means presented in this figure. Un-

Fig. 3. Relative response rate as a function of relative reinforcement access time for seven different pigeons from Experiment II. Each solid circle is the mean relative response rate for a single pigeon, over the last five sessions of a condition. The open circle is the mean for all birds over the last five sessions of the first condition. Symbols are as defined in Figure 1.

Table 2

Experimental conditions and data from Experiment II. The data are means from the last five sessions of each condition. Sessions were terminated after 40 reinforcements. L-left, R-right.

Subject	Condition	Sessions	Scheduled Rfts per Hour		Rft Duration (sec)		Obtained Rfts per Hour		Responses per Minute		Changeovers per Minute
			L	R	L	R	L	R	L	R	
P-1	1	32	30	30	3	3	30	27	47.6	63.0	10.5
P-2		31	30	30	3	3	30	34	34.0	42.1	7.8
P-3		32	30	30	3	3	30	27	66.3	64.4	9.1
P-4		33	30	30	3	3	35	35	49.4	54.6	10.2
P-5		32	30	30	3	3	25	30	33.4	32.1	6.8
P-6		41	30	30	3	3	36	29	51.0	48.8	8.7
P-7		32	30	30	3	3	30	28	45.0	39.0	6.2
P-1	2	50	30	30	4	2	31	30	47.0	22.5	8.9
P-2		26	20	40	3	3	18	45	22.6	52.5	5.1
P-3		29	10	50	2	4	10	51	13.1	84.7	3.7
P-4		49	50	10	3	3	50	8	58.6	7.7	1.5
P-5		22	40	20	2	4	33	23	34.7	41.8	6.6
P-6		35	20	40	2	4	16	39	19.4	74.7	4.0
P-7		20	40	20	5	1	36	2	76.7	0.4	0.1

like the data from the first experiment, these data points fall very near the diagonal matching line.

As in Experiment I, obtained rather than scheduled rates of reinforcement were used in calculating reinforcement access time. This method results in trivial matching under one condition where the bird stopped responding on the right key and hence received all reinforcements for left-key pecks (R_1). The right key in this condition was associated with a 1-sec magazine duration, and from observing the pigeon it was evident that this duration was too short to allow feeding to occur.

In Experiment I, the pigeons' eating behavior was monitored by a photobeam across the feeder opening and there also the 1-sec magazine duration allowed little or no feeding. Nonetheless, all three pigeons in that experiment continued to respond on the key associated with this duration for 35 sessions. The pigeon exposed to this condition in Experiment II, without previous exposure to a variety of other reinforcement rates and durations, virtually stopped responding for 1-sec feeder presentations by the tenth session.

GENERAL DISCUSSION

Experiment II demonstrates that relative response rate on concurrent VI VI schedules can, under certain conditions, match relative reinforcement access time. Unlike the pigeons of Experiment I and those of Todorov (1973) and Schneider (1973), the pigeons of Experiment II were not exposed to a succession of changing schedule conditions. Instead, each was exposed to only one schedule in which the rate and/or duration of reinforcement differed on the two keys, thus greatly reducing any possible interaction among conditions.

It is, of course, not certain that schedule interaction is entirely responsible for the different results. Other, presumably incidental, features of the procedure and apparatus may also play a part. The colors of the response keys, their distance from one another, constant-probability *versus* arithmetic VI schedules, may all be important variables, although none has been implicated by prior research.

The matching rule is based on relative rates of response in the steady state. To date, virtually no data have been reported on the transition from one concurrent schedule to

another. It might well be that systematic examination would yield a family of relative response functions that lie intermediate between an absence of schedule control, early in training, and matching in the steady state. Furthermore, a systematic examination of the effects of repeated changes in schedule parameters might reveal the degree to which the results of Todorov (1973), Schneider (1973), and our Experiment I reflect the influence of inelastic effects of varied frequency and duration of reinforcement.

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- Received 18 June 1974.
(Final Acceptance 18 April 1977.)