REINFORCEMENT RATE AND INTERRESPONSE TIME DIFFERENTIATION¹

DENNIS O. KUCH² AND JOHN R. PLATT

MCMASTER UNIVERSITY

Reinforcement rate and differential reinforcement of IRTs were independently manipulated to assess their relative contribution to the control of interresponse times (IRTs). Modified percentile reinforcement schedules (Platt, 1973) allowed control of reinforcement rate while longest or shortest IRTs were selectively reinforced. In the absence of differential IRT reinforcement, mean IRT decreased with increasing reinforcement rate. Compared to this small effect of reinforcement rate, reinforcement of long IRTs produced large changes in mean IRT at constant reinforcement rates. No interaction of reinforcement rate and IRT reinforcement was detected. The demonstration of large IRT changes in the absence of reinforcement-rate changes indicates the precedence of IRT reinforcement over molar reinforcement-rate correlations in the determination of IRTs in these procedures.

Key words: IRT reinforcement, reinforcement rate, response differentiation, shaping, response strength, key peck, pigeons

Two variables frequently implicated in the control of response rates and interresponse-time (IRT) distributions under a variety of reinforcement schedules are rate of reinforcement and differential reinforcement of IRTs (*e.g.*, Morse, 1966). Put somewhat more theoretically, it has often been speculated (*e.g.*, Norman, 1966) that reinforcement of an operant such as key pecking may influence subsequent occurrences of that operant by either one or both of two distinct processes. On the one hand, rate of reinforcement of key pecking may control the strength of that entire operant class, so that higher rates of reinforcement lead to higher rates of key pecking. On the other hand, any tendency for particular IRTs to be differentially reinforced may directly shape those IRTs. Unfortunately, procedures most often used to investigate one of these two possible functions of reinforcement frequently confound the other.

Reinforcement rate has most often been

investigated by varying the parameters of a variable-interval (VI) schedule of reinforcement. Response rates generally increase as a negatively accelerated function of reinforcement rate (Catania and Reynolds, 1968). These results seem to provide direct evidence for control of strength of key pecking by reinforcement rate, but it is well known that VI schedules tend differentially to reinforce IRTs, in the sense that longer IRT values have a higher conditional probability of being followed by food than do shorter ones (Morse, 1966; Reynolds and McLeod, 1970). Furthermore, the IRT value associated with a given probability of being followed by food is longer, the longer the value of the VI schedule. It is thus difficult to isolate the relative contributions of reinforcement rate and IRT differentiation in simple VI schedules.

The major efforts to unconfound reinforcement rate and IRT differentiation in VI schedules have involved synthetic VI schedules (Anger, 1956, 1973; Millenson, 1964; Shimp, 1973), which make food available in the same manner as a simple VI schedule but require the occurrence of a member of a particular IRT class for food actually to be delivered. Such schedules establish an upper limit on reinforcement rate in the same manner as simple VI schedules, while the actual reinforcement rate depends also on the subjects'

¹This research was supported by Grant A8269 from the National Research Council of Canada. Portions of the data have been reported by the first author in a doctoral dissertation submitted to McMaster University. Reprints may be obtained from John R. Platt, Department of Psychology, McMaster University, Hamilton, Ontario, Canada L8S 4K1.

²Now at the Department of Psychology, McGill University, Montreal, Quebec, Canada.

rate of emission of the required IRT classes. For example, Shimp (1973) obtained reinforcement rates ranging from 30 to 60 per hour over a variety of synthetic VI schedules that made reinforcement available at rates from 180 to 1894 per hour. In general, such studies offer evidence for the importance of IRT differentiation by showing variations in IRT distributions as a function of frequency of reinforcement of specific IRT classes. More recently, Shimp (1974) demonstrated unconfounded effects of reinforcement rate using synthetic VI schedules to hold IRT differentiation constant.

The IRT differentiation variable has been most often investigated by varying the value of a differential-reinforcement-of-low-rates schedule (DRL), which presents food following responses separated from the preceding response by more than some specified minimum interval. The IRT distribution is usually sharply peaked near the minimum value required for food presentation, unless that minimum value is large (Kramer and Rilling, 1970). Such results seem to provide evidence for the effectiveness of IRT differentiation, but the interpretation is complicated by the lower reinforcement rates produced when larger minimum IRT values are required for food presentation. For instance, the mean interval between food presentations increases with sharp positive acceleration over DRL schedules requiring minimum IRTs from 2 to 32 sec (Alleman, 1970).

The effects of reinforcement-rate variations on DRL performance can be controlled using interreinforcement intervals generated by pigeons on DRL schedules to construct yoked VI schedules with essentially the same sequences of interreinforcement intervals (Richardson, 1973). Although such yoked VI schedules do not eliminate preferential reinforcement of longer IRTs, they do specify a gradually increasing probability of reinforcement over IRT values, rather than the discrete demarcations between reinforced and nonreinforced values specified by DRL schedules. Richardson's results indicate the effectiveness of IRT differentiation, in that response rates on DRL schedules were always lower than on yoked VI schedules with essentially the same reinforcement rates.

The evidence is thus clear that differential reinforcement of IRTs and reinforcement rate can determine response rates. However, there

seem to be no studies that parametrically manipulated both reinforcement rate and differential reinforcement of IRTs to indicate the relative effectiveness of the two variables in determining responding. The present studies attempted to manipulate independently reinforcement rates and differential reinforcement of IRTs using a modification of the percentile reinforcement schedules developed by Alleman and Platt (1973). These modified, or interval-percentile schedules, have been described, by Platt (1974). In essence, these schedules use a bird's recent rate of responding to determine what proportion of key pecks would have to be followed by food to maintain a given rate of reinforcement. These reinforcements may then be assigned to responses without regard to IRT values so that effects of reinforcement rate may be observed in the absence of differential reinforcement of IRTs. These schedules also allow reinforcements to be assigned to extreme IRTs relative to the distribution of recently emitted IRTs, so as to reinforce differentially the longest or shortest IRTs being emitted while maintaining a prescribed rate of reinforcement.

EXPERIMENT I

METHOD

Subjects

Sixteen adult, experimentally naive, White Carneaux pigeons obtained from Palmetto Pigeon Plant were maintained at 80% of their free-feeding weights.

Apparatus

The experiment was conducted in four identical, three-key Lehigh Valley pigeon chambers. Only the center key was used. The key was mounted 19 cm above the floor and could be transilluminated with a No. 1820 incandescent bulb operated at 28 V dc. Experimental control and data acquisition were accomplished with a Digital Equipment Corporation PDP 8/e computer equipped to resolve real time to the nearest 0.02 sec. The computer recorded any closure of the pecking-key microswitch as a response, provided it was separated by at least 0.1 sec from the preceding closure.

Procedure

An autoshaping procedure was used to initiate key pecking (Brown and Jenkins, 1968). The birds were then randomly assigned to four groups, with the restriction that each group contain four birds. Throughout the remainder of the experiment, birds in a particular group were always scheduled to receive the same average interval between the first peck of a session, or the first peck after a food presentation, and the next food presentation. For the four groups, these intervals were 10, 30, 60, and 120 sec. These average intervals were chosen to reflect the range of food presentation rates reported by Catania and Reynolds (1968) to produce most of the variation in key-pecking rates for pigeons under simple VI schedules. In the present experiment, all food presentations were 3-sec access to mixed grain and a session always terminated with the thirtieth food presentation. During food presentations, the keylight was turned off and the food-hopper light was illuminated. The house-light remained on throughout a session.

The first 20 sessions, designated Baseline I, consisted of following key pecks with food at the scheduled average interval, without respect to IRT values. This was accomplished by programming the computer to hold in memory a list of the smallest number of most recent IRTs whose sum would be equal to or larger than twice the scheduled reinforcement interval. This length was chosen because it has been shown that a list containing an average of two reinforced IRTs provides a reasonable estimate of the current IRT distribution while remaining sensitive to sustained trends in that distribution (Alleman and Platt, 1973). Each key peck was then followed by food with a probability

$$P = t/T_m \quad (1)$$

where m was the number of IRTs held in memory, t was the sum of their duration and T was the schedule reinforcement interval. Thus, probability of food presentation was independent of the current IRT value and was determined instead by the relation of recent key-pecking rate to the scheduled rate of reinforcement. In this and subsequent phases of the experiment, the first key peck of a session and the first peck following a food presentation were never followed by food, nor were they

placed in the IRT memory list to determine subsequent food-presentation probabilities. Also, the IRT memory list was carried over from the end of one session to the beginning of the next.

The next 30 sessions of the experiment, designated Shaping I, consisted of half the birds in each group having food presented following their longest IRTs and half following their shortest IRTs, with the same scheduled reinforcement intervals as in Baseline I. This was accomplished by reinforcing an IRT only if it was more extreme than

$$k = (m + 1) [1 - (t/T_m)] \quad (2)$$

of the values in the IRT memory list where m , t and T have the same meaning as in Equation 1. Equation 2 has its origin in Alleman and Platt's (1973) demonstration that the proportion of IRTs followed by food, if only IRTs more extreme than k of the last m IRTs, eventuate in food presentation is given by

$$P = 1 - [k/(m + 1)] \quad (3).$$

Thus, setting the right-hand sides of Equations 1 and 3 equal to each other yields Equation 2, which specifies differential reinforcement of extreme IRTs and control of average reinforcement interval in the same manner as for the Baseline phase. This condition was followed by Baseline II, which consisted of 16 sessions under the same conditions as Baseline I. Then came 30 sessions of Shaping II, in which the opposite extreme of the IRT distribution from that used in Shaping I was followed by food. Finally, 16 sessions of Baseline III were administered under the same conditions as Baselines I and II.

RESULTS

Figure 1 plots mean IRT for each bird against blocks of two sessions through the course of the experiment. Separate axes were used for the data of birds scheduled for different reinforcement intervals, with the shortest intervals represented at the top of the figure and longer ones toward the bottom. Broken lines connect points obtained when shortest IRTs were selectively followed by food. In this and subsequent analyses, times from the beginning of a session or a food presentation to the subsequent key peck were not included as IRTs. When longest IRTs were followed by food, mean IRT gradually increased toward

Fig. 1. Mean interresponse times (IRTs) in blocks of two sessions for each bird.

asymptotic levels. The only exception was Bird 4 in the 10-sec condition, which increased its mean IRT for 12 sessions, but then returned to near baseline values. The increases in mean IRT when longest IRTs were followed by food tended to become larger across conditions, so that birds in the 120-sec condition showed much greater increases than birds in the 10-sec condition. When baseline conditions were reinstated after shaping of long IRTs, mean IRT rapidly fell to near baseline values. Following shortest IRTs by food did not consistently produce an obvious trend away from baseline IRT means.

The left panel of Figure 2 further summarizes IRT data by showing mean IRT for each reinforcement interval condition, with separate functions connecting means for the last three sessions of Baseline I and the last six sessions during which longest and shortest IRTs were followed by food. An analysis of variance, comparing mean IRTs at the end of Baseline I with those obtained when shortest IRTs were followed by food, indicated that the small increase in mean IRT with reinforcement interval was statistically significant, $F(3, 12) = 5.51$,

$p < 0.025$, as was the slight tendency for mean IRTs to be shorter when shortest IRTs were followed by food; $F(1, 12) = 7.48$, $p < 0.025$. The interaction of these two variables was not reliable; $F(3, 16) < 1.0$. An additional analysis of variance compared mean IRTs at the end of Baseline I with those obtained when longest IRTs were followed by food. The increase in mean IRT with scheduled reinforcement interval was again significant; $F(3, 12) = 12.12$, $p < 0.001$. In addition, mean IRTs were longer when longest IRTs were followed by food; $F(1, 12) = 74.11$, $p < 0.001$; and the magnitude of this effect increased with reinforcement interval; $F(3, 16) = 6.75$, $p < 0.005$.

For comparison with other studies, the right panel of Figure 2 shows the data of the left panel replotted as response rate *versus* reinforcement rate. Plotted in this manner, the small effect of following shortest IRTs by food becomes more apparent, as does the effect of reinforcement rate in the Baseline phase. Also included in the Figure are the results of Catania and Reynolds (1968) for arithmetic VI schedules. Higher response rates are shown for the current Baseline phase than for

Fig. 2. Left panel shows mean IRT as a function of scheduled reinforcement interval in the last three sessions of Baseline I and the last six sessions during which longest and shortest IRTs were followed by food. Right panel shows the same data replotted as response rate *versus* reinforcement rate and also includes the results of Catania and Reynolds (1968) for arithmetic VI schedules.

Catania and Reynolds' VI, but it should be remembered that the latter include postreinforcement pauses while the former do not.

Figure 3 provides a more detailed picture of IRT differentiation by showing IRT distributions for each bird over the last three sessions of Baseline I and the last six sessions, during which longest IRTs were followed by food. Birds that received short reinforcement intervals are represented on the left side of the figure, those receiving longer intervals are to the right. Baseline IRT distributions were sharply peaked with a mode at less than 1 sec. In addition, Birds 9, 10, and 14 displayed a secondary peak between 1 and 2 sec. The major change in baseline IRT distributions as reinforcement interval increased appeared to be a slight increase in the length of their positive tails. When longest IRTs were followed by food, IRT distributions were generally bimodal. The lower peak of these distributions was at less than 1 sec and appeared to correspond to the baseline IRT distribution. The

second peak fell at higher values and displayed greater dispersion at longer reinforcement intervals. Bird 4 in the 10-sec condition displayed no second peak. Birds 14, 15, and 16 in the 120-sec condition displayed such high dispersion in the upper part of the IRT distribution that a second mode was not readily discernible.

Table 1 shows the mean reinforced IRT at the end of each condition for each bird. When shortest IRTs were selectively followed by food, the mean reinforced IRT was between 0.1 and 0.2 sec and showed no systematic relationship to scheduled reinforcement interval. The distributions of reinforced IRTs, which are not shown, were almost completely contained below 0.3 sec. In the Baseline phase, the mean reinforced IRTs were somewhat longer and showed a systematic increase with scheduled reinforcement interval. The distribution of reinforced IRTs was essentially identical to the Baseline IRT distributions shown in Figure 3. When longest IRTs were selectively fol-

Fig. 3. IRT distributions for each bird in the last three sessions of Baseline I and the last six sessions during which longest IRTs were followed by food.

lowed by food, mean reinforced IRTs were much longer than in the Baseline phase and increased sharply with scheduled reinforcement interval. Distributions of reinforced IRTs were generally symmetrical and confined to the upper tails of the IRT distributions shown in Figure 3.

Table 1

Mean reinforced interresponse times (IRTs) in seconds for the last three sessions of Baseline I and the last six sessions during which longest and shortest IRTs were followed by food.

Reinforcement Interval (sec)	Bird	IRT Reinforcement		
		Shortest	Baseline	Longest
10	1	0.14	0.60	5.32
	2	0.18	0.87	4.08
	3	0.13	0.90	3.73
	4	0.18	0.66	1.97
	Mean	0.18	0.76	3.77
30	5	0.21	0.53	6.59
	6	0.11	0.84	9.05
	7	0.24	1.15	9.95
	8	0.10	0.72	7.18
	Mean	0.16	0.81	8.19
60	9	0.19	0.93	9.15
	10	0.19	1.17	10.45
	11	0.14	0.83	15.69
	12	0.10	0.85	12.11
	Mean	0.15	0.95	11.85
120	13	0.21	1.81	12.92
	14	0.22	0.92	32.99
	15	0.10	1.10	18.95
	16	0.10	1.72	23.45
	Mean	0.16	1.39	22.07

Figure 4 indicates the degree to which mean reinforcement interval was controlled by the present procedures. Mean obtained reinforcement interval is plotted against the scheduled interval for the last three sessions of Baseline I and the last six sessions during which longest and shortest IRTs were followed by food. In general, mean reinforcement intervals were very close to their scheduled values. The only notable deviations occurred when longest IRTs were followed by food. In this case, mean reinforcement interval became slightly larger than scheduled values as the scheduled value increased. The maximum deviation was 9.4 sec at a scheduled value of 120 sec. Distributions of obtained reinforcement intervals showed little variation between birds and had similar shapes across scheduled reinforcement intervals. Figure 5 thus typifies obtained rein-

forcement interval distributions by showing the average distributions for the 120-sec condition at the ends of the second Baseline phase and the phases during which longest and shortest IRTs were followed by food. In Baseline phases, and when shortest IRTs were followed by food, these distributions were approximately exponential. They thus resemble those for constant probability VI or random-interval schedules (Catania and Reynolds, 1968). When longest IRTs were followed by food, reinforcement interval distributions were of similar shape, except for a deficiency in very short intervals. This deficit was responsible for the slightly larger mean reinforcement intervals when longest IRTs were followed by food, and it occurred because, as longer and longer IRTs were selected for reinforcement, the shortest reinforcement interval obtainable was correspondingly increased. Although the small deviations in mean reinforcement interval could not have contributed substantially to the large mean IRT values obtained when longest IRTs were followed by food, the deficit of very short intervals could have been important. However, this deficit could not have played an important role in the initial shaping of long IRTs, because the deficit became substantial only after the occurrence of long IRTs. Furthermore, Catania and Reynolds (1968, Experiments 2 and 3) reported changes in overall response rate as a function of variation in short reinforcement intervals on VI schedules that are very small relative to the difference obtained between Baseline and long IRT reinforcement phases of the present experiment.

Results reported thus far indicate a relatively small effect of reinforcement interval on IRTs, and a very large effect of following longest IRTs by food. Since the procedures left the number of key pecks per reinforcement uncontrolled, it is of some importance to ask if confounded variations in this factor could be responsible for any of the apparent effects of reinforcement interval or of IRT differentiation. Figure 6 shows the mean proportion of IRTs followed by food at each reinforcement interval for the last three sessions of Baseline I and the last six sessions during which longest and shortest IRTs were followed by food. These proportions decreased with reinforcement interval and were higher when longest IRTs were followed by food. If decreasing the proportion of IRTs followed by food increases

Fig. 4. Mean obtained reinforcement interval as a function of scheduled interval in the last three sessions of Baseline I and the last six sessions during which longest and shortest IRTs were followed by food.

Fig. 5. Distributions of obtained reinforcement interval averaged over the four birds in the 120-sec condition during the last three sessions of Baseline II and the last six sessions during which longest and shortest IRTs were followed by food.

mean IRT, it is possible that this confounded variable contributed to the apparent effect of reinforcement interval, but not to the finding of longer IRTs when longest IRTs were followed by food.

EXPERIMENT II

The results of Experiment I indicated clear effects of both reinforcement rate and differential reinforcement of longest IRTs, although

Fig. 6. Mean proportions of IRTs followed by food as a function of scheduled reinforcement interval in the last three sessions of Baseline I and the last six sessions during which longest and shortest IRTs were followed by food.

the latter effects were considerably larger than the former. In addition, these two variables appeared to exert quite different effects on IRT distributions. When reinforcements were assigned without regard to IRT values, IRT distributions usually displayed a single peak at less than 1 sec and lower reinforcement rates tended to lengthen the positive tail above this peak. When longest IRTs were differentially reinforced, IRT distributions generally displayed a second peak at some value beyond 2 sec. This second peak tended to fall at higher IRT values with lower reinforcement rates, while the location of the first peak remained fixed at less than 1 sec.

The effect on location of the second peak of IRT distributions when longest IRTs were differentially reinforced may have resulted either from variations in reinforcement rate or from differences in the relative extremity of IRTs reinforced. Platt (1973) referred to this latter factor as selectivity of differential reinforcement. The reinforcement interval conditions of Experiment I differed in both reinforcement rate and selectivity, although the within-group effects are ascribable solely to selectivity. When longest IRTs were reinforced, larger average reinforcement intervals assigned reinforcements to a smaller and more extreme portion of the IRT distribution. For example, consider a bird in the 10-sec condition and one in the 120-sec condition, both of which were emitting IRTs with a mean of 1 sec. The bird in the 10-sec condition would receive food following the longest 0.10 of its IRTs, while the bird in the 120-sec condition would receive food following only the longest 0.0083 of its IRTs. Longer mean IRTs for a bird in the 120-sec condition could thus be due to reinforcement for longer IRTs on the average, rather than to any tendency for the effectiveness of differential reinforcement to depend on reinforcement rate. Selectiveness of differential reinforcement and reinforcement rate were thus confounded across reinforcement interval groups.

Experiment II sought to unconfound the effects of selectivity of IRT reinforcement from those of reinforcement rate during the differential reinforcement of longest IRTs. To this end, birds exposed to 10-sec reinforcement intervals in Experiment I were used. These birds were exposed to a series of conditions in which the average scheduled reinforcement interval

was always 120 sec. The conditions varied as to whether reinforced IRTs were selected from the entire distribution, the same portion of the distribution as for the 10-sec condition of Experiment I, or the same portion of the distribution as for the 120-sec condition of Experiment I. Reinforcement interval was held constant at 120 sec across these three conditions by appropriate variations in the proportion of selected IRTs actually reinforced.

METHOD

Subjects and Apparatus

Birds 1 to 4 from Experiment I continued to be maintained at 80% of their free-feeding weights. Apparatus was identical to that for Experiment I.

Procedure

All birds were first exposed for 13 sessions to the baseline condition of the 120-sec group in Experiment I. Thus, Equation 1 was used to schedule reinforcement intervals averaging 120 sec without regard to the values of IRTs reinforced. During the next 32 sessions, longest IRTs were selected for reinforcement in the same manner as for the 10-sec condition of Experiment I by assigning T a value of 10 in Equation 2. However, only a random $\frac{1}{12}$ of these selected IRTs were actually followed by food so as to produce an average reinforcement interval of 120 sec. This condition was designated as a random ratio 12 of the 10-sec shaping condition, or RR 12 (10). For the final 32 sessions, longest IRTs were reinforced in the same manner as for the 120-sec condition of Experiment I by presenting food following all IRTs meeting the requirements of Equation 2 with $T = 120$. This condition was designated RR 1 (120).

RESULTS

Summary statistics were computed on the last three sessions of the Baseline condition and the last six sessions of the RR 12 (10) and RR 1 (120) conditions. Figure 7 shows IRT distributions at the end of each condition for each of the four birds. Baseline distributions were again unimodal with a mean of 0.9 sec, which was significantly larger than the mean of 0.6 sec displayed by these birds during their last 10-sec baseline; $t(3) = 3.81$, $p < 0.05$. The RR 12 (10) condition produced bimodal IRT distributions with first peaks reminiscent of

the shortest baseline IRTs and second peaks in the range of 3 to 4 sec. The mean of these distributions was 2.8 sec, which was significantly larger than for the immediately preceding baseline; $t(3) = 4.83$, $p < 0.05$. But this mean did not differ significantly from the mean IRT of 2.0 sec displayed by these birds when longest IRTs were reinforced in the 10-sec condition of Experiment I; $t(3) = 1.34$.

The IRT distributions for the RR 1 (120) condition resembled those for the RR 12 (10) condition, except that the second peaks were displaced to larger values and showed greater dispersion. The mean IRT of 5.3 sec for the RR 1 (120) condition was significantly larger than the mean of 2.8 sec for the RR 12 (10) condition; $t(3) = 2.63$, $p < 0.05$. The former mean was also somewhat smaller than that of 8.6 sec displayed by birds in the 120-sec condition of Experiment I, when longest IRTs were followed by food. This discrepancy may have resulted from the long history of less-favorable shaping conditions experienced by the present

birds before being exposed to the RR 1 (120) condition.

Additional results of this experiment were similar to those for Experiment I. Mean obtained reinforcement intervals were well controlled with values of 123, 124, and 116 sec for the Baseline, RR 12 (10) and RR 1 (120) conditions, respectively. These values did not differ significantly; $F(2, 9) < 1.0$. This removes any remaining doubt that slightly longer reinforcement intervals when longest IRTs were reinforced might have confounded the results of Experiment I.

DISCUSSION

The results are consistent with existing literature in that both reinforcement rate and differential reinforcement of IRTs affected the IRTs of pigeons' key pecks. Variations in key-peck IRTs produced by variations in reinforcement rate were relatively small, but as large as those that have been reported for VI schedules

Fig. 7. IRT distributions for each bird in the last three sessions of the Baseline condition and the last six sessions of the RR 12 (10) and RR 1 (120) conditions.

with similar reinforcement rates (Catania and Reynolds, 1968, Figure 25). Selectively following shortest IRTs with food had very small effects, but following longest IRTs by food produced large increases in the values of emitted IRTs comparable to those reported for DRL schedules over the range of 2 to 32 sec (Alleman, 1970, Experiment I).

The divergence of functions relating IRT means to reinforcement intervals for the baseline conditions and the conditions in which longest IRTs were selectively followed by food might appear to represent a strong interaction between reinforcement rate and IRT differentiation in Experiment I. Such an interaction could mean that a food presentation was more effective in shaping the IRT it followed, the lower the overall rate of reinforcement (Brandon, 1969). However, such a conclusion cannot be drawn from Experiment I, because birds receiving lower reinforcement rates also tended to receive food following a more highly selected proportion of their IRTs when longest IRTs were followed by food.

Experiment II eliminated this confounding of selectiveness of differential reinforcement and reinforcement rate. When IRTs from the same portion of the distribution as for the 10-sec condition of Experiment I were selected for reinforcement, similar mean IRTs were produced, in spite of the fact that only a random $\frac{1}{12}$ of these selected IRTs were actually followed by food, so as to produce a reinforcement rate comparable to the 120-sec condition of Experiment I. In fact, this result might be taken to question the existence of even a main effect of reinforcement rate when longest IRTs are selectively reinforced. In any case, the apparent interaction of IRT differentiation and reinforcement rate in Experiment I is actually a simple effect of the selectiveness of the differential reinforcement criteria. Alleman and Platt (1973, Experiment II) reported a similar finding for the apparent interaction of IRT differentiation with proportion of key pecks reinforced.

Our results thus indicated strong effects of differentially reinforcing longest IRTs, much smaller effects of reinforcement rate, and no interaction between these two variables. Furthermore, these two variables exerted their influence on response rate in different ways. Increasing reinforcement rate appeared to decrease the extent of the positive tails on a pri-

mary peak of the IRT distribution with a modal value under 1 sec. Increasing the relative extremeness of longest IRTs selected for reinforcement increased the central tendency and dispersion of a second peak of the IRT distribution with a modal value beyond 2 sec. The distinctiveness of effects of these two variables on IRT distributions provides further evidence for the existence of distinct underlying processes.

These results may have some implications for the possible roles of reinforcement rate and IRT differentiation in more traditional reinforcement schedules, such as DRL and VI. Applicability to DRL schedules is relatively straightforward. When longest IRTs were selectively followed by food in the present experiments, the situation could be characterized as a DRL t schedule, in which the value of t was changed from time to time to hold reinforcement rate constant. Since IRT differentiation proved to be the critical process in a series of successive approximations to higher and higher values of t , it is reasonable to conclude that this process is critical to the effect of any single one of those t values. Conversely, the relatively small effects of reinforcement rate and the lack of any interaction of this variable with IRT differentiation strongly suggest that differences in performance as a function of t value on DRL schedules is only minimally determined by confounded variations in reinforcement rate, at least within the range of 30 to 360 reinforcements per hour. These findings are thus consistent with Richardson's (1973) demonstration that DRL schedules generate longer IRTs than VI schedules yoked to have the same interreinforcement intervals. They extend Richardson's findings by providing baselines free of any differential reinforcement of IRTs, and by providing direct comparisons of the relative magnitude of effects produced by variations in reinforcement rate and IRT differentiation.

Application to VI schedules is less clear. The present schedules resemble VI schedules in their assignment of food presentations to responses in time, but they differ from VI schedules in assigning these reinforcements with equal probability to any IRT that occurred. Traditional VI schedules assign higher conditional probabilities of reinforcement to longer IRTs (Morse, 1966). The effects of reinforcement rate in the present situation thus support

the assumed role of this variable as the determinant of VI performance, but do not eliminate the possibility that IRT differentiation is also involved in VI schedules. If IRT differentiation were effective in VI schedules, one would expect higher response rates from the present baseline conditions than from VI schedules with the same reinforcement rates, because the latter favor reinforcement of longer IRTs. As a matter of fact, response rates from the current baseline conditions were consistently higher than those reported by Catania and Reynolds (1968, Figure 25) for VI schedules with similar reinforcement rates, but other differences between these studies prevent a direct comparison.

Those present conditions that followed longest IRTs by food also differed critically from VI schedules in that these conditions specified an abrupt increase from zero to unity reinforcement probability as IRT duration increased. Their effectiveness in shaping long IRTs is consistent with the assumption of a role for IRT differentiation in VI schedules. However, the gradual increase in reinforcement probability with IRT duration generated by VI schedules would presumably be much less favorable to IRT differentiation. A definitive assessment of the contribution of IRT differentiation to VI performance thus awaits comparison of VI performance with that generated by a schedule containing similar distributions of reinforced responses in time, but with no differential reinforcement of IRTs.

The results also raise some issues as to the basic mechanisms by which reinforcement acts selectively to strengthen response classes. One such issue is raised by the finding that IRT mean always approached asymptotic values when longest IRTs were followed by food. The values of these asymptotes appeared to be determined by the relative extremity of longest IRTs selected for reinforcement, but why were asymptotes generated at all? Since the present procedure always reinforced the longest IRTs being emitted, traditional accounts of response shaping (*e.g.*, Keller and Schoenfeld, 1950, pp. 189-190) would not appear to imply any limit to the resulting shaping process. Unfortunately, our results do not allow a definitive statement as to the basis of these shaping limits. However, some possibilities can be discarded and others suggested.

The limits on IRT shaping that we observed bring to mind the claims (*e.g.*, Malott and Cumming, 1964, p. 325; Shimp, 1968, p. 532) that longer IRTs are less affected by reinforcement or are less preferred by the organism. Our findings are consistent with these claims, but the claims are little more than restatements of the results. If either claim is accepted, the question then becomes one of why longer IRTs are less susceptible to reinforcement or are less preferred.

One possible basis for an upper limit to IRT shaping would be the loss of effectiveness of reinforcement at low rates of reinforcement like those occurring on DRL schedules. Such a factor could not have played a major role in determining the shaping limits observed in these experiments because the procedures were successful in holding reinforcement rates nearly constant over the range of IRT values actually shaped.

Another possible basis for the shaping limits observed is that a larger proportion of the IRT distribution encountered reinforcement as emitted IRTs became longer. The resulting reductions in relative extremity of IRTs reinforced may have eventually produced insufficient differential reinforcement to support further shaping. However, Alleman and Platt (1973) have demonstrated similar IRT shaping limits when constant proportions of IRTs were selectively reinforced.

Two additional possible bases for the observed shaping limits are both closely related to the increased dispersion of IRT distributions with increases in their central tendency, just as has been observed for other temporal response dimensions (*e.g.*, Catania, 1970; Platt, Kuch, and Bitgood, 1973). Because a list of recent IRTs was used to estimate percentile points on the IRT distribution for purposes of assigning reinforcements, the dispersions of the resulting distributions of reinforced IRTs were determined both by the length of that list and the dispersions of the IRT distributions. Because the latter increased as shaping progressed, it became more and more likely that a relatively short IRT would occasionally be reinforced—a factor that could have eventually prevented further shaping. Since longer IRT lists would reduce dispersion in the distributions of reinforced IRTs, list length may well be a factor in the determination of shaping limits.

The increase in dispersion of IRT distributions with central tendency also suggests another possible basis for observed shaping limits. This relation between dispersion and central tendency may reflect a decrease in the discriminability of IRT values as the absolute value of the IRTs increases. Decreased discriminability of IRTs at larger values could produce increased responding at subcritical values. The plausibility of such an account could be assessed by looking for higher shaping limits with the addition of stimuli that serve to differentiate subcritical from reinforceable time values, or by examining a particular response dimension (e.g., spatial) in which dispersion is not related to central tendency.

The fact that our procedures were effective in shaping longer IRTs raises an even more fundamental issue concerning the mechanism by which reinforcement acts selectively to strengthen response classes. Alleman and Platt (1973) found that pigeons increased their mean IRT when food selectively followed a constant proportion of emitted IRTs in the upper extreme of their IRT distributions. These lower response rates constituted a self-imposed delay of reinforcement or reduction in reinforcement rate. This result might be attributed to a positive feedback loop in Alleman and Platt's experiments, whereby increases in mean IRT produced reductions in reinforcement rate, which in turn produced further decreases in mean IRT. In having effectively controlled reinforcement rates, the experiments reported here indicate that such a loop is not necessary to the shaping of long IRTs. Both the present results and those of Alleman and Platt are comprehensible within the framework of a traditional law of effect. Within limits, the probability of IRTs followed by food increased while the probability of other IRTs decreased. As a matter of fact, Platt (1973) argued that procedures such as those used in the present experiments and by Alleman and Platt represent a more direct rendering of the law of effect than traditional operant paradigms. It is not as clear to us how recent positions (e.g., Baum, 1973; Herrnstein, 1970) advocating abandonment of the law of effect in favor of a system of organismic economics based on molar correlations between response rate and reinforcement rate would deal with such results.

REFERENCES

- Alleman, H. D. *Interresponse-time reinforcement*. Unpublished doctoral dissertation, University of Iowa, 1970.
- Alleman, H. D. and Platt, J. R. Differential reinforcement of interresponse times with controlled probability of reinforcement per response. *Learning and Motivation*, 1973, 4, 40-73.
- Anger, D. The dependence of interresponse times upon the relative reinforcement of different interresponse times. *Journal of Experimental Psychology*, 1956, 52, 145-161.
- Anger, D. The effect upon simple animal behavior of different frequencies of reinforcement, part II: separate control of the reinforcement of different IRTs. *Journal of the Experimental Analysis of Behavior*, 1973, 20, 301-312.
- Baum, W. M. The correlation-based law of effect. *Journal of the Experimental Analysis of Behavior*, 1973, 20, 137-153.
- Brandon, P. *The effects of error-contingent time-out on counting behavior in rats*. Unpublished doctoral dissertation, University of Michigan, 1969.
- Brown, P. L. and Jenkins, H. M. Auto-shaping of the pigeon's key-peck. *Journal of the Experimental Analysis of Behavior*, 1968, 11, 1-8.
- Catania, A. C. Reinforcement schedules and psychophysical judgments: A study of some temporal properties of behavior. In W. N. Schoenfeld (Ed.), *The theory of reinforcement schedules*. New York: Appleton-Century-Crofts, 1970. Pp. 1-42.
- Catania, A. C. and Reynolds, G. S. A quantitative analysis of responding maintained by interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, 1968, 11, 327-383.
- Herrnstein, R. J. On the law of effect. *Journal of the Experimental Analysis of Behavior*, 1970, 13, 242-266.
- Keller, F. S. and Schoenfeld, W. N. *Principles of psychology*. New York: Appleton-Century-Crofts, 1950.
- Kramer, T. J. and Rilling, M. Differential reinforcement of low rates: A selective critique. *Psychological Bulletin*, 1970, 74, 225-254.
- Malott, R. W. and Cumming, W. W. Schedules of interresponse time reinforcement. *Psychological Record*, 1964, 14, 211-252.
- Millenson, J. R. A further investigation of the correlation between IRT frequency and IRT reinforcement distributions. *Psychonomic Science*, 1964, 1, 373-374.
- Morse, W. H. Intermittent reinforcement. In W. K. Honig (Ed.), *Operant behavior: areas of research and application*. New York: Appleton-Century-Crofts, 1966. Pp. 52-108.
- Norman, M. F. An approach to free-responding on schedules that prescribe reinforcement probability as a function of interresponse time. *Journal of Mathematical Psychology*, 1966, 3, 235-268.
- Platt, J. R. Percentile reinforcement: Paradigms for experimental analysis of response shaping. In G. H. Bower (Ed.), *The psychology of learning and motivation: advances in theory and research*, Vol. 7. New York: Academic Press, 1973. Pp. 271-296.
- Platt, J. R., Kuch, D. O., and Bitgood, S. C. Rats' lever-press durations as psychophysical judgments of

- time. *Journal of the Experimental Analysis of Behavior*, 1973, **19**, 239-250.
- Reynolds, G. S. and McLeod, A. On the theory of interresponse-time reinforcement. In G. H. Bower (Ed.), *The psychology of learning and motivation: advances in theory and research*, Vol. 4. New York: Academic Press, 1970. Pp. 85-107.
- Richardson, W. K. A test of the effectiveness of the differential-reinforcement-of-low-rate-schedule. *Journal of the Experimental Analysis of Behavior*, 1973, **20**, 385-391.
- Shimp, C. P. Magnitude and frequency of reinforcement and frequencies of interresponse times. *Journal of the Experimental Analysis of Behavior*, 1968, **11**, 525-535.
- Shimp, C. P. Synthetic variable-interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, 1973, **19**, 311-330.
- Shimp, C. P. Time allocation and response rate. *Journal of the Experimental Analysis of Behavior*, 1974, **21**, 491-499.

Received 8 December 1975.

(Final Acceptance 4 June 1976.)