

*EFFECTS OF VARIATIONS IN LOCAL REINFORCEMENT  
RATE ON LOCAL RESPONSE RATE IN  
VARIABLE INTERVAL SCHEDULES*

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Rats trained to lever press for sucrose were exposed to variable-interval schedules in which (i) the probability of reinforcement in each unit of time was a constant, (ii) the probability was high in the first ten seconds after reinforcement and low thereafter, (iii) the probability was low for ten seconds and high thereafter, (iv) the probability increased with time since reinforcement, or (v) the probability was initially zero and then increased with time since reinforcement. All schedules generated similar overall reinforcement rates. A peak in local response rate occurred several seconds after reinforcement under those schedules where reinforcement rate at this time was moderate or high ([i], [ii], and [iv]). Later in the interreinforcement interval, local response rate was roughly constant under those schedules with a constant local reinforcement rate ([i], [ii], and [iii]), but increased steadily when local reinforcement rate increased with time since reinforcement ([iv] and [v]). Postreinforcement pauses occurred on all schedules, but were much longer when local reinforcement rate was very low in the ten seconds after reinforcement ([iii]). The interresponse time distribution was highly correlated with the distribution of reinforced interresponse times, and the distribution of postreinforcement pauses was highly correlated with the distribution of reinforced postreinforcement pauses on some schedules. However, there was no direct evidence that these correlations resulted from selective reinforcement of classes of interresponse times and pauses.

*Key words:* variable-interval schedules, random-interval schedules, local response rate, local reinforcement rate, postreinforcement pauses, lever press, rats

Under interval schedules of reinforcement, the probability of the next response being reinforced will vary with the time since the last response and with the time since the last reinforcement. It is therefore possible that either time variable may function as a discriminative stimulus controlling response probability. The influence of probability of reinforcement at a particular time since the last reinforcement was investigated by Catania and Reynolds (1968, Experiment 3). Using pigeons and grain reinforcement, they examined rate of responding as a function of time since reinforcement on several variable-interval (VI) schedules with different distributions of interreinforcement intervals. Under two schedules in which the probability of reinforcement increased as a function of time since reinforcement, local response rate also increased. With a constant-probability VI schedule, however, in which there is no such increase in lo-

cal reinforcement probability, response rates changed little with time since reinforcement. Introducing extra short intervals in a VI schedule markedly increased the rate of responding immediately after reinforcement. They concluded that local rate of reinforcement (i.e. the probability of reinforcement integrated over a short period of time) controls response rate but this effect generalizes to earlier and later times. They also suggested that smoother relations between local rate of responding and local rate of reinforcement will be obtained if the opportunities for reinforcement are closely and uniformly spaced along the continuum of time since reinforcement.

Harzem, Lowe, and Priddle-Higson (1978) replicated some of Catania and Reynold's findings. Using rats and milk reinforcement, they found that local response rate remained roughly constant as a function of time since reinforcement on a constant-probability VI schedule, but increased markedly on an arithmetic VI schedule. On the latter schedule the intervals form an arithmetic series, and the probability of reinforcement increases with

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time since reinforcement. Harzem, Lowe, and Priddle-Higson also demonstrated a reliable postreinforcement pause on these schedules, which was attributable to unconditioned suppressive aftereffects of the reinforcer and appeared unrelated to the probability of reinforcement at that time.

The present study attempted an extensive investigation of the relation between local rate of reinforcement and local rate of response that went beyond previous studies in several ways. Computer control made it possible to generate schedules in which reinforcers were stochastically available every second, thus creating a continuous series of opportunities for reinforcement as recommended by Catania and Reynolds. Local response rates were collected second-by-second (compared with intervals of several seconds used by Catania and Reynolds, and 11- or 8.5-sec intervals used by Harzem et al.) because preliminary studies suggested that marked transient changes in response rate occur shortly after reinforcement. The subjects, rats, were trained on schedules which incorporated two of the variables studied by Catania and Reynolds in pigeons: the probability of reinforcement either remained constant or increased with time since reinforcement, and there either were or were not extra short intervals in the schedule. This latter variable was extended, however, by introducing schedules with an unusually low number of short intervals. Altogether there were five schedules: a random interval (RI) schedule (which is equivalent to a constant-probability VI; Millenson, 1963), modified RI schedules in which the probability of reinforcement in the 10 sec after reinforcement was either higher or lower than at other times, and arithmetic VI schedules which either did or did not contain occasional short interreinforcement intervals.

In addition to the local response rate data, the distributions of postreinforcement pauses and interresponse times (IRTs) and the distributions of reinforced postreinforcement pauses and IRTs were collected. The postreinforcement pause data were analysed to see whether, as Harzem, Lowe, and Priddle-Higson suggest, the pauses are insensitive to the probability of reinforcement in the first few seconds of the interreinforcement interval. The IRT data were examined to see whether selective reinforcement had influenced the distri-

bution. If, as Anger (1956) and Shimp (1973) argue, schedules have their effects primarily by arranging for certain classes of IRTs to be reinforced, then there should be a high correlation between the overall IRT distribution and the distribution of reinforced IRTs. If the correlation is low or zero, it suggests that IRT reinforcement is not a significant determinant of behavior under the complex interval schedules studied here.

## METHOD

### *Subjects*

Four experimentally naive male hooded rats, aged 60 days at the start of the study, were maintained at 80% of their free-feeding weights and were caged singly with water always available.

### *Apparatus*

In a Campden Instruments Model 410 test chamber fitted with a dipper feeder, only the left lever was operative and required a force of .1 N to register a lever press. The chamber was illuminated by 2.8-W houselight. The reinforcer was 3-sec access to 5% sucrose solution (by weight), timed from the operation of a switch attached to the clear plastic flap covering the food tray. During sucrose availability the tray was lit by a 2.8-W light. The chamber was situated inside a sound-attenuating housing that was fitted with a ventilating fan that masked extraneous noise. The experiment was controlled and the data collected by a Data General Nova 2/10 minicomputer programmed in ACT (Millenson, 1975).

### *Procedure*

Sessions were conducted five days a week and each lasted until 100 reinforcers had been obtained. Following initial shaping of lever pressing with sucrose reinforcers, rats were given two sessions of reinforcement of every lever press and then exposed to variable-interval schedules. The sequence of the several schedules, which are described below, and the numbers of sessions under each are given in Table 1. Each condition continued until the subject's behavior showed no systematic changes across the last five sessions and the response rate on each of those sessions was within 10% of the mean.

Table 1

Sequence of experimental conditions and number of sessions in each condition for each subject

	Rat 1	Rat 2	Rat 3	Rat 4
Random interval	92	91	91	92
Random interval (high-low)	45	45	78	75
Random interval	27	27	30	32
Random interval (low-high)	64	66	79	75
Variable interval	51	50	60	57
Variable interval (no zero interval)	33	29	30	30
Random interval	28	30	28	28

*Random interval.* After each second a reinforcement was set up with a nominal probability of  $1/32$  and then delivered dependent upon the next lever press. Once a reinforcer had been set up the program halted and no other reinforcer could be programmed until it had been collected. The obtained sequence of interreinforcement intervals, generated by a hardware probability generator, was truly random, in that it did not consist of a repeated finite sequence, but averaged 28.5 sec rather than 32 sec. All the schedules used subsequently were adjusted to give an equivalent rate of reinforcement.

*Random interval (high-low).* On three occasions in the 10 sec immediately following reinforcement, at 0 sec, 3.6 sec, and 7.2 sec, a reinforcer was set up with a probability of  $25/128$ . Thereafter, a reinforcer was set up after each second with a probability of  $1/64$ .

*Random interval (low-high).* On three occasions in the 10 sec immediately following reinforcement, at 0 sec, 3.6 sec, and 7.2 sec, a reinforcer was set up with a probability of  $1/128$ . Thereafter, a reinforcer was set up after each second with a probability of  $3/64$ . The values used in these complex RI schedules were determined by three constraints: the reinforcement rate must be the same as in the basic RI schedule; after the first 10 sec, opportunities for reinforcement must be 1 sec apart; only multiples of  $1/128$  could be used for programming probabilities.

*Variable interval.* Interreinforcement intervals of 0, 8, 16, 24, 32, 40, 48, and 56 sec occurred with equal probability in a random sequence.

*Variable interval (no zero interval).* Interreinforcement intervals of 4, 12, 20, 28, 36, 44, and 52 sec occurred with equal probability in a random sequence. A consequence of each possible reinforcement interval occurring with equal frequency is that on these variable-inter-

val schedules, but not the random-interval schedules, the probability of a reinforcer being set up in the next interval of time increases with time since reinforcement. Another difference is that the variable-interval schedules each contain a maximum interreinforcement interval (56 or 52 sec).

## RESULTS

The various schedules generated different local reinforcement rates. The obtained interreinforcement times on each schedule are shown in Figure 1. The statistic presented is the number of reinforcements per opportunity for 2-sec intervals over the 30 sec immediately after reinforcement. Reinforcements per opportunity is calculated as the reinforcers at that time since reinforcement, divided by the total at that time or later. On a computer-generated random-interval schedule, this measure should not vary as a function of time since reinforcement. However, the obtained reinforcements per opportunity does vary a little because of variations in responding. All the data presented are means of the last four sessions in each condition. The data in Figure 1 are the means across rats. Individual data are not presented because the rats' patterns of behavior could only slightly alter the reinforcements per opportunity functions generated by the schedules, and variability between rats was consequently low.

The function for the unmodified random-interval schedule is flat except for the first 2-sec period where it is depressed. This deviation results from postreinforcement pausing, which is discussed later. The high-low random-interval and low-high random-interval functions differ from the unmodified random interval in that each contains a marked change in reinforcements per opportunity at 10 sec after reinforcement. Following these transitions,

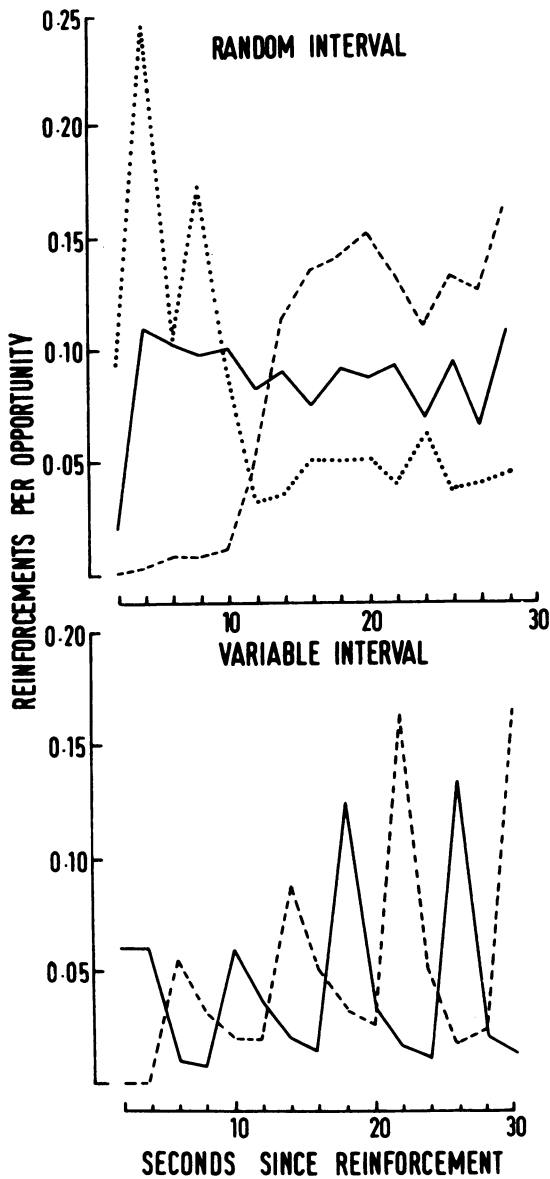


Fig. 1. Mean obtained reinforcements per opportunity functions for the five schedules. Upper panel shows functions for random interval (solid line), high-low random interval (dotted line), and low-high random interval (dashed line). Lower panel shows functions for variable interval (solid line) and variable interval (no zero interval) (dashed line).

the functions are roughly flat and lie below and above the unmodified random-interval function respectively. The fluctuation at the beginning of the high-low random-interval curve results from the 3.6-sec separation between occasions on which reinforcement can be set up. As rats responded relatively rapidly,

reinforcers were normally obtained within 2 sec of being made available. Consequently, the probability of reinforcement in the sixth second, for example, was very low as a reinforcer could be set up after 3.6 sec or 7.2 sec but not at any point in between.

A similar effect is seen in the variable-interval functions (Figure 1, lower panel). Under these schedules there was always 8 sec between moments at which reinforcement could be set up, resulting in a regular fluctuation in the reinforcements per opportunity functions. It can also be seen that there is an upward trend in the functions with time since reinforcement, unlike the random-interval functions. Relative to the ordinary variable-interval function, the variable interval with no zero interval function is displaced half a cycle (4 sec) to the right.

Local response rates on the random-interval schedule are shown in Figure 2. On initial exposure to this schedule, the response rate of all rats increased steeply from zero in the first second to a peak in the fifth second following reinforcement and then subsided to an intermediate steady rate. As both the increase and the subsequent decrease in local response rate occurred within the first 10 sec following reinforcement, regression equations were calculated for time since reinforcement on local response rate, based on data from the 11th to 32nd seconds. The slopes of the regression lines are given in Table 2. For two subjects these do not differ from zero and for the other two there is a significant negative slope. That is, the rate of response declined with time since reinforcement.

The consistent pattern of behavior on initial exposure to the random-interval schedule was not reinstated when the rats were returned to this baseline condition for the last time more than 200 sessions later. While Rats 2 and 3 showed a similar pattern but at lower response rates, the other two lost the initial peak. All subjects showed a substantial reduction in overall response rate over the later phases of the experiment, but this effect was dramatic for Rat 1. The reason for the decline in rates is not clear, but it is possibly the lengthy exposure to schedules in which there were very few short interreinforcement intervals.

Local response rates as a function of time since reinforcement on the high-low random-interval and low-high random-interval sched-

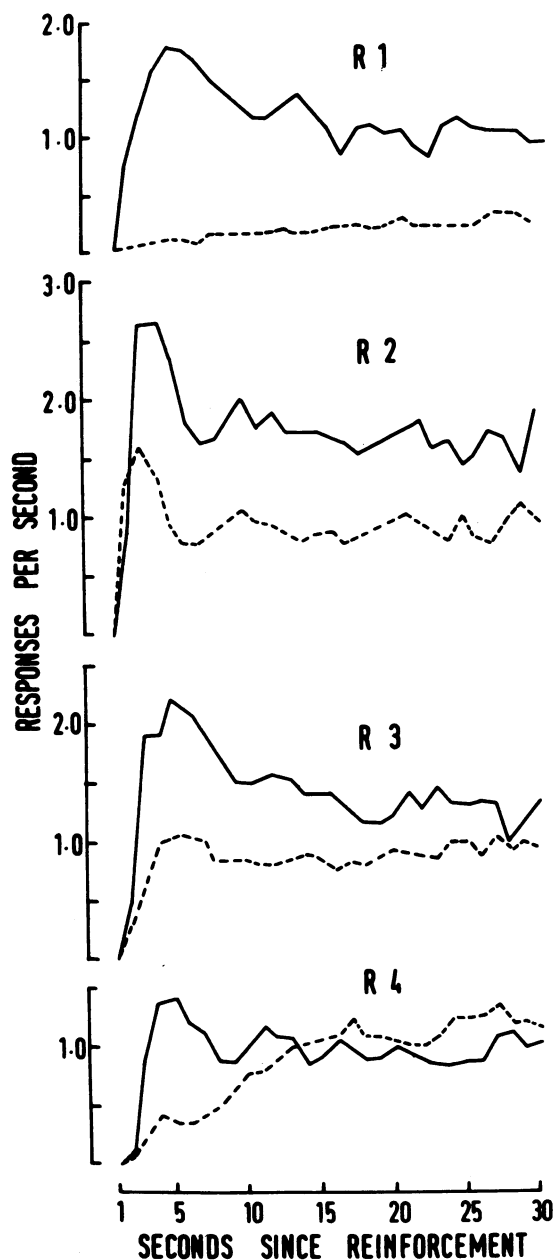


Fig. 2. Local response rates on first (solid lines) and final (dashed lines) exposure to unmodified random interval schedule.

ules are shown in Figure 3. On the high-low random interval, the functions are similar to those on the preceding random-interval schedule, although slightly more variable. The primary difference is that the steady local response rate seen between 15 sec and 30 sec after reinforcement is lower than before. This corresponds to the difference in reinforcement

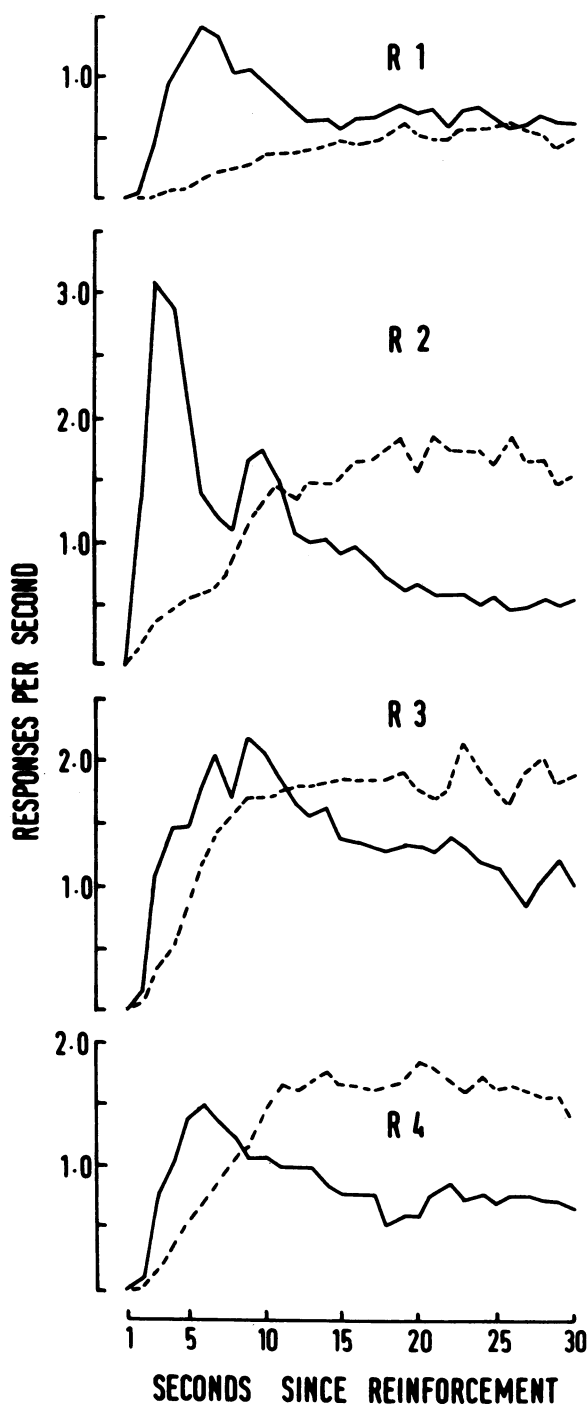


Fig. 3. Local response rates on high-low random interval (solid lines) and low-high random interval (dashed lines) schedules.

rate at this time on the two schedules. The slopes of the regression lines, calculated as before, were significantly negative for each sub-

Table 2  
Slopes of regression lines of local response rate on time since reinforcement between 10 and 32 seconds.

	Rat 1	Rat 2	Rat 3	Rat 4
Random interval	-.014*	-.005	-.014*	-.004
Random interval (high-low)	-.007**	-.034***	-.034***	-.011**
Random interval (low-high)	+.007**	+.009	0	-.006
Variable interval	+.005***	+.024***	+.021***	+.036***
Variable interval (no zero interval)	+.005***	+.024***	+.019***	+.047***

\* $p < .05$ \*\* $p < .01$ \*\*\* $p < .001$ 

ject on the high-low random-interval schedule (see Table 2).

The very small number of opportunities for reinforcement within 10 sec of reinforcement on the low-high random interval schedule (see Figure 1) had a marked effect. Local response rate increased slowly until it reached an asymptote at around 15 sec after reinforcement. In three cases this asymptotic rate was considerably greater than at the corresponding period

on the high-low random interval schedule. The exception was Rat 1 which showed continual drops in overall rate with each succeeding experimental phase. The slopes of the regression lines (for the 11th to 32nd seconds) were not significantly different from zero for three subjects and positive for Rat 1.

Local response rates on the variable-interval and variable interval with no zero interval schedules are shown in Figure 4. Under the variable-interval schedule there was an initial peak in responding, a drop, and then a slow steady increase in rate with time since reinforcement. Under the variable interval with no zero interval schedule, there was a similar steady increase in rate with time since reinforcement, but the initial peak in rate was absent. On both these schedules, all subjects showed a significant positive slope for regression lines calculated on data from the 11th to 32nd seconds (see Table 2).

Summarizing these data for the five schedules used, early peaks in local response rate occurred on the random-interval, high-low random-interval, and variable-interval schedules, but not on the low-high random-interval or variable interval with no zero interval schedules. Table 2 shows that following the first ten seconds after reinforcement, local response rate tended to decline or remain steady on random-interval, high-low random-interval, and low-high random-interval schedules and to increase on variable-interval and variable interval with no zero interval schedules.

On all the schedules, local response rate was zero in the first second following reinforcement. Median postreinforcement pause values for each subject in four of the experimental conditions are given in Table 3. Three subjects show a consistent pattern in which the value for the low-high random interval is much longer than the other three, and the value on final exposure to random interval is

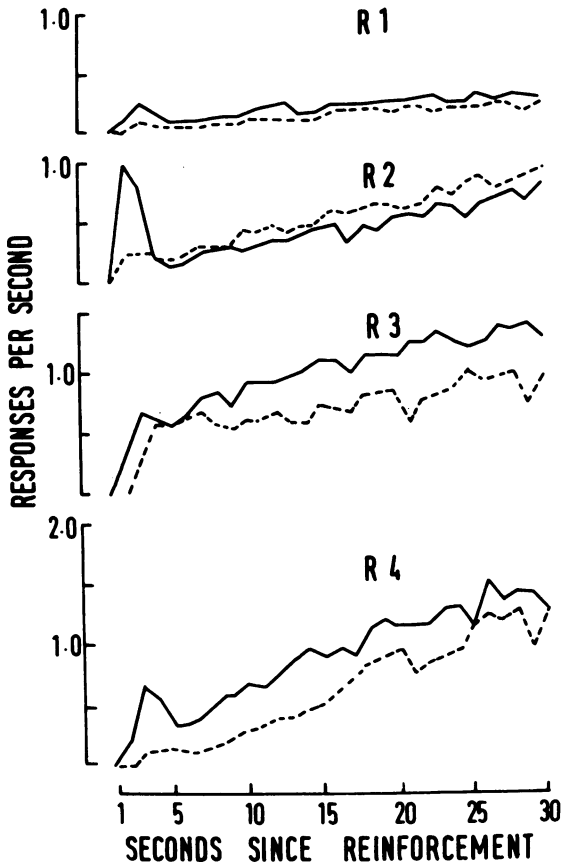


Fig. 4. Local response rates on variable-interval (solid lines) and variable-interval (no zero interval) (dashed lines) schedules.

Table 3

Median postreinforcement pauses (seconds) in the second, third, fourth, and seventh conditions in Table 1.

	Rat 1	Rat 2	Rat 3	Rat 4
Random interval (high - low)	2.90	1.45	2.82	2.55
Random interval	5.02	1.56	2.35	2.47
Random interval (low - high)	13.25	5.83	5.79	6.22
Random interval	11.29	3.75	3.19	4.58

rather longer than on previous exposure to this schedule. The exception is Rat 1 which showed very long postreinforcement pauses on all but the first of these schedules.

For the last three conditions, variable interval, variable interval with no zero interval, and random interval, IRT distributions and the distributions of reinforced IRTs were collected in 1-sec class intervals. Table 4 shows the Pearson product-moment correlation coefficient,  $r$ , between these two measures, calculated for IRTs from 0 to 12 sec. For three subjects, Rats 2, 3, and 4, there were large positive correlations. Rat 1 showed nonsignificant correlations.

Also shown in Table 4 are correlations between frequencies of postreinforcement pauses of different lengths (grouped into 1-sec class intervals) and the frequency with which those postreinforcement pauses were reinforced for the three different random-interval schedules (data from the second, third, and fourth experimental conditions were used). These were based on all postreinforcement pauses of less than 12 sec. As there were instances of there being no postreinforcement pauses in certain 1-sec class intervals,  $N$  is less than 12 in most cases. Large positive correlations were obtained on the random-interval and high-low

random-interval schedules, but three out of four correlations were nonsignificant on the low-high random-interval schedule. This reflects the fact that although many post-reinforcement pauses were less than 12 sec on the latter schedule (see Table 2), there were very few opportunities for reinforcement in this period (see Figure 1).

DISCUSSION

The present study attempted a fine-grain analysis of the relationship between local reinforcement rate and local response rate on several variable-interval schedules that differed in the distributions of interreinforcement intervals that they provided. This analysis revealed that later in the interreinforcement interval local reinforcement rate strongly influences local response rate, but shortly after reinforcement its influence is limited.

Later in the interval, local response rates tracked local reinforcement rates in that they were steady on random-interval schedules and increased with time on variable-interval schedules. This replicated, and provided more detailed quantification of, results reported by Catania and Reynolds (1968) for pigeons, and by Harzem, Lowe, and Priddle-Higson (1978)

Table 4

Pearson product-moment correlation coefficient,  $r$ , between IRTs and reinforced IRTs up to 12 sec ( $N = 12$  in every case), and between PRPs and reinforced PRPs (values of  $N$  are given).

	Rat 1	Rat 2	Rat 3	Rat 4
IRTs:				
Variable interval	.36	.76**	.87***	.98***
Variable interval (no zero interval)	.45	.79**	.81**	.98***
Random interval	.39	.92***	.89***	.97***
PRPs:				
Random interval	.74**	.95***	.91***	.96***
$N$	11	12	10	9
Random interval (high - low)	.90***	.99***	.80**	.97***
$N$	10	5	10	10
Random interval (low - high)	-.02	0	.68*	.51
$N$	9	12	10	10

\* $p < .05$     \*\* $p < .01$     \*\*\* $p < .001$

for rats. Additionally, it was found that the local response rate varied with the local reinforcement rate on the various random-interval schedules.

There were, however, features of behavior in the first 10 sec after reinforcement that were unrelated to the local reinforcement rate. On the unmodified random-interval schedule, where local reinforcement rate was constant throughout the interreinforcement interval, responding accelerated rapidly from zero in the first second to a maximum in the fifth before declining to an intermediate steady rate. The initial rate reflected a brief but reliable postreinforcement pause that occurred although the reinforcer has minimal discriminative properties on this schedule. Harzem, Lowe, and Priddle-Higson (1978) observed a similar pause and suggested that it is an unconditioned suppressive aftereffect of the reinforcer. This conclusion was indirectly supported in the present study, because when the schedule was changed to high-low random interval, greatly increasing the probability of reinforcement within a few seconds of reinforcer delivery, postreinforcement pauses were unchanged.

The peak in responding that followed the postreinforcement pause was not observed by Harzem, Lowe, and Priddle-Higson, but they used 8.5- or 11-sec measurement intervals which would have obscured it. Again this phenomenon is not attributable to local reinforcement rate, and again it was insensitive to the increase in local reinforcement rate on high-low random interval. The peak was eliminated, however, by the schedules in which very short interreinforcement intervals were rare (low-high random interval and variable interval with no zero interval). It therefore seems that such a peak is generated as long as there are some short interreinforcement intervals. A possible explanation of the peak is provided by the natural rate hypothesis (Harzem, Lowe, & Spencer, 1978; Staddon, 1972). According to this view, there is a natural response rate for a given species and response topography, and if the subject withholds responding for a period of time, in this case the postreinforcement pause, there may be a subsequent compensatory increase in rate.

In summary, there is a brief postreinforcement pause that cannot be eradicated by the availability of reinforcement at that time,

immediately followed by a peak in responding that can only be eradicated if the availability of reinforcement approaches zero at that time. After this, local response rate tracks local reinforcement rate.

Unusual features of this study were that on some schedules opportunities for reinforcement were very close together in time (1 sec), and on all schedules the obtained reinforcements per opportunity functions were recorded. Figure 1 shows that on the variable-interval schedules, where opportunities for reinforcement were separated by 8 sec, the obtained reinforcements per opportunity functions fluctuate markedly. Comparison with Figure 4, however, reveals that local response rates did not track these fluctuations in reinforcements per opportunity. Instead, they increased fairly steadily. This finding supports earlier assertions, based on less detailed information, that the effects of reinforcement at a particular time will generalize to earlier and later times (Catania & Reynolds, 1968). Limits on such generalization are seen in Figure 3, where the large change in local reinforcement rate that always occurred 10 sec after reinforcement produced a considerable change in local response rate around that time.

For several schedules IRT distributions were strongly skewed towards short IRTs, as is typically found on variable-interval schedules. For Rats 2, 3, and 4 these distributions were highly correlated with the distributions of reinforced IRTs. This was not the case for Rat 1 which responded at very low rates. Although very low correlations would have indicated that the selective reinforcement of IRTs was not influencing performance, these high correlations cannot readily be interpreted. On the schedules used in the present study, and any schedule which does not specify which IRTs are eligible for reinforcement (Shimp, 1973), it is not possible to tell whether certain IRT classes have increased in frequency because they are more often reinforced, or whether they are more often reinforced because they are more frequent.

Similar problems attend the interpretation of the relation between postreinforcement pause distributions and the corresponding distributions of reinforced postreinforcement pauses. All rats had high correlations on the random-interval and high-low random-interval schedules, although, as pointed out earlier,



pausing seemed insensitive to increases in reinforcement density. The correlation presumably results from the fact that these schedules reinforce postreinforcement pauses in rough proportion to their frequency. On the low-high random-interval schedule this is no longer true, because of the very small number of short interreinforcement intervals, and the correlations disappear.

The demonstration of orderly relations at the molecular level of local response rates and local reinforcement rates was a general feature of this study. If such orderly relations exist, they are in a sense more fundamental than relations at the molar level of overall response and reinforcement rates. This is because the overall rates are summary statistics that can be derived (as weighted averages) from the local rates, while the local rates cannot be derived from the overall rates. However, Herrnstein's (1961, 1970) quantification of the law of effect, which has successfully systematized data from a wide range of schedules (de Villiers, 1977), operates at the molar level. Herrnstein (1970) and de Villiers (1977) support the molar level of analysis by citing studies where orderly relations were not seen at the molecular level, although overall response rates did match overall relative reinforcement rates. In contrast, the present study demonstrated clear effects of local reinforcement rate changes while overall reinforcement rate was held constant.

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