

RATS' PERFORMANCE ON VARIABLE-INTERVAL SCHEDULES WITH A LINEAR FEEDBACK LOOP BETWEEN RESPONSE RATE AND REINFORCEMENT RATE

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Three experiments investigated whether rats are sensitive to the molar properties of a variable-interval (VI) schedule with a positive relation between response rate and reinforcement rate (i.e., a VI+ schedule). In Experiment 1, rats responded faster on a variable ratio (VR) schedule than on a VI+ schedule with an equivalent feedback function. Reinforced interresponse times (IRTs) were shorter on the VR as compared to the VI+ schedule. In Experiments 2 and 3, there was no systematic difference in response rates maintained by a VI+ schedule and a VI schedule yoked in terms of reinforcement rate. This was found both when the yoking procedure was between-subject (Experiment 2) and within-subject (Experiment 3). Mean reinforced IRTs were similar on both the VI+ and yoked VI schedules, but these values were more variable on the VI+ schedule. These results provided no evidence that rats are sensitive to the feedback function relating response rate to reinforcement rate on a VI+ schedule.

Key words: feedback function, interresponse time, variable-interval schedule, variable-ratio schedule, lever press, rats

Accounts of the behavior observed when an organism is exposed to a free-operant schedule of reinforcement can be categorized into two broad classes. One class of account contains those views that stress the importance of the moment-to-moment variations in response-reinforcer contiguity (i.e., molecular theories). The other class contains those accounts that stress the overall correlation between responding and reinforcement as critical in determining performance (i.e., molar theories). Both of these classes of account have been applied, with some success, to the behavior observed on free-operant schedules of reinforcement.

The molecular views attempt to explain performance by reference to the reinforcement of particular interresponse times (IRTs) by the operative schedule (e.g., Morse, 1966; Peele, Casey, & Silberberg, 1984). On a variable-interval (VI) schedule, reinforcement is more probable the longer the pause since the last response. Hence, on such a schedule, long IRTs are differentially reinforced, and overall response rates are low as a consequence of the increase in such long IRTs. In contrast, on variable-ratio (VR) schedules, no

such differential reinforcement of long IRTs occurs. Indeed, it may be that, given the tendency of organisms to respond in bursts separated by pauses, short IRTs are more likely to be reinforced on such a schedule, as there are relatively more short than long IRTs emitted (see Ferster & Skinner, 1957; Pear & Recor, 1979). As long IRTs are not reinforced differentially on VR schedules, overall rates should be higher on this type of schedule than on a VI schedule. This finding has been noted even when the reinforcement rates obtained on the two schedules have been matched (see Cole, 1994; Ferster & Skinner; Peele et al.; Zuriff, 1970).

Such a molecular interpretation of free-operant performance has also been supported by experiments that deliberately reinforce particular IRTs. For example, Peele et al. (1984) noted that the rates of response on VI and VR schedules became more similar to one another when the length of the reinforced IRT on these schedules was equated through a yoking procedure. Additionally, evidence from the study of many different contingencies has shown that organisms' responding can be maintained by contiguous response-reinforcer pairings, even when this leads to a reduction in the overall rate at which reinforcement is obtained (see Reed & Schachtman, 1989; Vaughan & Miller, 1984). Such evidence suggests that organisms are not particularly sensitive to the overall rela-

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tion between responding and reinforcement, but rather they are more sensitive to local response-reinforcer pairings.

In contrast to the above molecular interpretation of schedule performance, molar interpretations stress the relation between the rate of response and the rate at which reinforcement is obtained as a determinant of performance on free-operant schedules (e.g., Baum, 1973, 1981). On a VR schedule, the faster the organism responds the faster reinforcement will be obtained. Thus, high rates of responding are differentially reinforced on such a schedule. In contrast, once an organism is emitting over a certain minimum level of responses on a VI schedule, further increases in the rate of response will not produce increases in the rate of reinforcement; that is, a VI does not differentially reinforce high rates of response. If subjects are sensitive to such molar relations, then a VR schedule would be expected to produce higher rates of response than a VI schedule, even given equivalent reinforcement frequencies.

Molar views of schedule performance have been supported by some studies concerning free-operant performance on a schedule which has the molecular properties of a VI schedule (i.e., it differentially reinforces long IRTs), but which also has the molar properties of a VR schedule (i.e., it differentially reinforces high rates of responding). McDowell and Wixted (1986) termed this schedule a VI schedule with a positive feedback loop relating response rate to reinforcement rate (a VI+ schedule). The VI+ schedule is temporally based (i.e., it reinforces the first response following a set period of time) and so will tend to reinforce long IRTs as does a standard VI schedule (the longer the organism pauses from responding, the more probable it is that the criterion interval will have elapsed). This schedule, however, also reinforces high rates of responding by determining the length of the interval between reinforcements according to the response rate. The faster the local response rate (i.e., responses per minute since the delivery of the last reinforcement), the shorter the mean interval value becomes. Human subjects responding on such a VI+ schedule exhibited almost identical rates of response to that which they emitted on a VR schedule with the same feedback function relating responding

to reinforcement. This result suggests a sensitivity to the molar properties of the schedule rather than to the molecular properties of the schedule. The feedback function relating response rate to reinforcement rate was identical on the two schedules, but the length of the reinforced IRTs was assumed to be unequal. Unfortunately, McDowell and Wixted did not report a measure of the reinforced IRTs for either the VR or the VI+ schedules studied in their experiment to demonstrate this latter point.

Unambiguous interpretation of the above result is complicated further as no comparison was made with a simple VI condition within the same experiment. It may be that the use of human subjects by McDowell and Wixted (1986) meant that the behavior observed on the schedules was not under schedule control, and that these subjects would have responded as quickly on any schedule presented to them. This is not an unlikely explanation of the results for two reasons. First, it is known that human performance on free-operant schedules can differ from that of nonhumans (see Wearden, 1981); and second, in a study of the effects of a VI+ schedule on rats' instrumental performance, Reed, Soh, Hildebrandt, DeJongh, and Shek (2000) noted that response rates generated by such a VI+ schedule were lower than those rates engendered by a VR schedule with a similar response-reinforcer feedback function. Similarly, Cole (1999) exposed rats to a range of VR and VI reinforcement schedules and to two versions of the VI+ schedule. Response rates on both of the versions of the VI+ schedule were similar to those on the VI schedule, and all three of the schedules led to lower response rates than those on the VR schedules when the reinforcement rates were equivalent. Additionally, the lengths of the reinforced IRTs on the VI+ schedules were similar to those on VI schedules, and were much longer than those produced by the VR schedule. This latter finding was also obtained by Reed *et al.* (2000).

The above results suggest that the rat subjects were not sensitive to the VI+ schedule, as these subjects did not respond at an appropriately high rate. Of course, this suggestion is valid only if the rats' behavior did contact the VI+ contingency. That is, the question needs to be addressed regarding

whether the rat subjects did experience the higher rates of reinforcement that could have been produced on the VI+ schedules by their responding at appropriately high rates. Unfortunately, there is little data available that would confirm whether or not this was the case in either the report by Cole (1999) or Reed et al. (2000).

Given the above limitations and unanswered questions regarding the reports produced by McDowell and Wixted (1986), Cole (1999), and Reed et al. (2000), the present study aimed to provide three important extensions to this line of investigation. First, it examined data from the acquisition of responding on a VI+ schedule, as well as from steady-state performance on such a schedule. Such an examination is critical so as to evaluate whether the rats do, in fact, make contact with the contingencies on a VI+ schedule. Second, it investigated the effects of direct yoking of reinforcement rates on VI+ and VI schedules. In the report by Cole, performance across different types of schedules (i.e., VR, VI+, and VI) was compared when reinforcement rates on those schedules were similar to one another. Direct yoking of reinforcement rates on these schedules, however, was not attempted. It would seem important to be able to show that these conclusions also hold when reinforcement frequencies are directly yoked across the schedules. Finally, this study made some detailed analyses of the reinforcement of IRTs on the various schedules in order to see if this aspect of behavior on the schedules may be related to overall rates of response.

EXPERIMENT 1

The first experiment attempted a systematic replication of the findings of McDowell and Wixted (1986) using rat subjects. Rats were trained to respond on a VR schedule prior to transfer to a VI+ schedule with a feedback function equivalent to the preceding VR schedule. Following this exposure to a VI+ schedule, the rats were returned to the VR schedule. If the results of McDowell and Wixted were to be replicated, then the rats should show similar rates of response on both schedules. However, if the results of Cole (1999) and Reed et al. (2000) were confirmed, the rats should show a lower rate of

response on the VI+ schedule than on the VR schedule. This design also allowed examination of the VR-to-VI+ transition performance to ascertain if the rats were contacting the positive portion of the VI+ schedule feedback function.

METHOD

Subjects

Three male Lister hooded rats served. Each was 12 to 13 months old at the start of training, had a free-feeding body-weight range of 535 to 575 g, and was maintained at 85% of this weight throughout the experiment. The rats had a history of food-reinforced, instrumental training on various schedules, but were naive to the schedules employed in the present study. They also had previously served in an observational learning experiment in which they had pushed a joystick and experienced tone stimuli. The rats were housed together in a group of three with water constantly available in the home cage.

Apparatus

Three identical operant conditioning chambers (Campden Instruments Ltd.) were used. Each chamber measured 23.5 cm by 23.5 cm by 20.5 cm and was housed in a light- and sound-attenuating case ventilated by a fan that provided background masking noise (65 dB[A]). Each chamber had two levers, both of which were permanently inserted into the chamber, but only one of which (the left) was operative during the experiment. A force of 0.343 N was required to depress the lever and close a microswitch. Jeweled houselights (not used in this experiment) were located above each of the levers. Reinforcement, which consisted of one 45-mg standard Noyes food pellet, was delivered to a centrally located, recessed food tray that was covered by a clear Perspex, hinged flap. The chamber was not illuminated during the course of the experiment. The experimental events were controlled by Paul Frey SPIDER software run on a BBC series B microcomputer.

Procedure

The rats received some preliminary lever press training using two 20-min sessions of a

continuous reinforcement (CRF) schedule. All the rats then responded on a VR schedule. This phase of the experiment was conducted for 30 sessions, with each session lasting for 60 min. The first session of training was VR-5 (range 1 to 9), the next session a VR-10 (range 1 to 19), the next two sessions were VR-15 (range 1 to 29), the next two sessions were VR-20 (range 1 to 39), and the following two sessions were VR-25 (range 1 to 49). Thereafter, the VR value was 30 (range 1 to 59) for the remainder of the first phase of training. In all of the VR schedules, the probability of each response being reinforced was set at a value of $1/\text{ratio}$, with the constraint that not more responses than the maximum range value could be emitted without receiving reinforcement.

Following this phase of the study, the rats were transferred to a VI+ schedule. This phase of training lasted for 20 sessions with each session lasting for 60 min. The mean interval required for reinforcement on the VI+ schedule was determined on-line by the equation

$$\text{Interval for reinforcement} = (i/n)*b, \quad (1)$$

where i was the interval between the last reinforcer to the present response; n was the total number of responses emitted during that period; and b was the equivalent VR value, which was set at 30 for the entire phase of the study. Once the mean interval was established according to this equation, the scheduling of reinforcement was determined by a random timer. The probability of a reinforcer being available at any particular second was $1/x$, where x was the mean interval as determined by the above equation. The VI+ schedule required that at least two responses be made for reinforcement: one to determine the interreinforcement interval and a second to collect the reinforcer.

Some examples may demonstrate how the VI+ schedule operates. Assume that the time from the last reinforcer was 60 s, and that 60 responses had been made during that time. In this case, the interval to reinforcement would equal $(60/60)*30 = 30$ s. During this 30 s, at 60 responses per minute, 30 responses would be emitted before the interval would time out. If 30 responses had been made during that 60 s period, then the interval would be: $(60/30)*30 = 60$ s. During this 60 s, if

responses were being emitted at 30 responses per minute, then 30 responses would be emitted prior to the reinforcer. Alternatively, if 120 responses had been made during the 60 s period, the interval became: $(60/120)*30 = 15$ s. During this 15 s, at 120 responses per minute, then 30 responses would be emitted prior to the reinforcer. Thus, the interval varies inversely with the rate of responding, and each reinforcer is delivered for about 30 responses.

The rats were then returned to the VR 30 schedule during Phase 3, which lasted for twenty 60-min sessions. Following this phase of training, the VR value was increased, in steps of five every two sessions, until the rats were responding on a VR 60 schedule (range 1 to 119). The rats then received twenty 60-min sessions on this schedule. They were then transferred to a VI+ schedule, as described above, but with a feedback function value equivalent to a VR 60 schedule. They received 20 sessions on this schedule, and were finally returned to the VR 60 schedule for a further 40 sessions.

RESULTS AND DISCUSSION

The response rates, reinforcement rates, and reinforced IRTs of all 3 rats in all six phases of the experiment are displayed in Figure 1. Rates of responding during exposure to the VI+ schedule, with a feedback function equivalent to a VR 30 schedule, were lower than that maintained by the VR 30 schedule. Following the introduction of the VI+(30) schedule, rates of responding decreased considerably from those in the previous VR 30 phase. On the reintroduction of the VR 30 schedule, rates of response returned to their baseline levels.

Rates of response were somewhat higher on the VR 60 schedule than on the preceding VR 30 schedule. Rates of responding fell on the introduction of the VI+(60) schedule, where a feedback function was equivalent to the VR 60 schedule. Response rate returned to baseline VR 60 levels for only one rat (R58) on the reintroduction of the VR 60 schedule. For R59, rates of responding only partially recovered during the final phase of VR 60 training, and were somewhat higher than at the end of the previous VI+(60) schedule. Response rates did not recover, however, for R60.

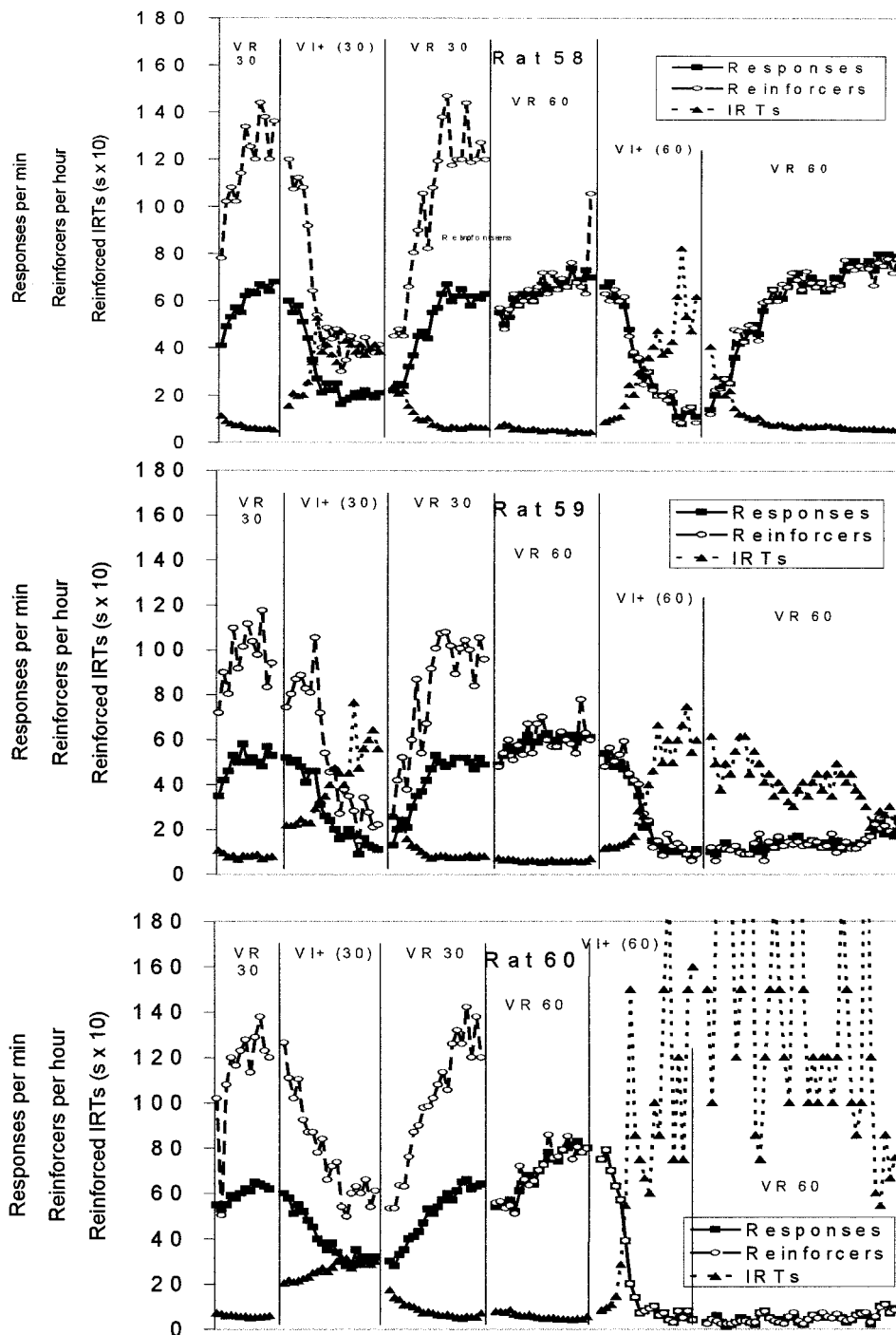


Fig. 1. Results from Experiment 1. Response rates, reinforcement rates, and reinforced IRTs (in seconds) for each of the three rats over sessions each phase of the study: VR 30; VI+(30); VR 30; VR 60; VI+(60); VR 60.

Table 1

Regression equations (and variance accounted for) describing the response-reinforcer feedback functions for the schedules in Experiment 1.

Subject	VR 30	VI+(30)	VR 60	VI+(60)
R58	-0.03 * 0.034 resp 93.5%	-0.01 * 0.033 resp 99.0%	0.05 * 0.016 resp 87.1%	0.01 * 0.016 resp 98.0%
R59	0.09 * 0.030 resp 79.6%	0.09 * 0.028 resp 90.0%	0.01 * 0.017 resp 97.2%	0.01 * 0.018 resp 95.8%
R60	-0.15 * 0.036 resp 80.3%	-0.04 * 0.036 resp 94.0%	0.01 * 0.017 resp 99.5%	0.01 * 0.017 resp 99.9%

Inspection of the rates of reinforcement obtained at the end of each phase reveals that rats obtained a higher rate of reinforcement on the VR schedules than they did on the corresponding VI+ schedules. In fact, by the end of training on the VI+(60) schedule, rates of reinforcement approached zero for all three rats. This finding goes some way to explaining the lack of a recovery of responding in the final phase of VR 60 training for R59 and R60: essentially, these rats had extinguished responding during exposure to the VI+ schedule. It is important to note that, at the start of both of the VI+ phases, rates of reinforcement were only slightly lower than in the previous VR schedule. This suggests that responding on the VI+ schedules did provide comparably high rates of reinforcement, at least initially. The data show that the mean reinforced IRT value was much lower on the VR schedule than on the equivalent VI+ schedule for all rats (except during the final VR 60 phase).

To confirm that the feedback functions relating response rate to reinforcement rate functioned as anticipated in the VR and VR+ schedules, the rate of reinforcement produced by a particular rate of response, for each of the four schedules employed, over all sessions of training are displayed in Table 1

for each rat. Inspection of these feedback functions relating rates of reinforcement to rates of response shows that the function was virtually identical across the VR 30 and VI+(30) schedules, and between the VR 60 and VI+(60) schedules. This suggests that the VI+ schedule was operating as programmed to provide a linear relation between increases in rate of response and increases in the rate of reinforcement. Despite this equivalent relation to the VR schedule feedback function, however, the VI+ schedule did not support as high rates of response as the former schedule (see Figure 1).

The top panel of Figure 2 shows the relation between the mean reinforced IRT and the response rate for each session of the study for all three rats. Not surprisingly, there is a strong correlation between these two measures. Inspection of the bottom panel of Figure 2, however, shows a similarly strong relation between the response rate on a particular session and the mean IRT on the preceding session. In fact, the latter correlation is statistically significantly stronger than the former, $z = 3.179$, $p < .0001$. This pattern of results for each individual rat can be seen in Table 2, which shows the regression equations and correlations relating the mean reinforced IRT to the response rates for each

Table 2

Relation between response rate and reinforced IRTs.

Rat	Response rate and IRT from Session	Response rate and IRT from Session-1	Z score for r Difference
R58	Log Rate = 1.69 - 0.65 Log IRT $r = 0.943$	Log Rate = 1.67 - 0.66 Log IRT $r = 0.953$	0.662 $p = 0.268$
R59	Log Rate = 1.64 - 0.74 Log IRT $r = 0.917$	Log Rate = 1.65 - 0.77 Log IRT $r = 0.959$	2.78 $p = 0.003$
R60	Log Rate = 1.67 - 0.83 Log IRT $r = 0.906$	Log Rate = 1.67 - 0.77 Log IRT $r = 0.959$	3.15 $p = 0.01$

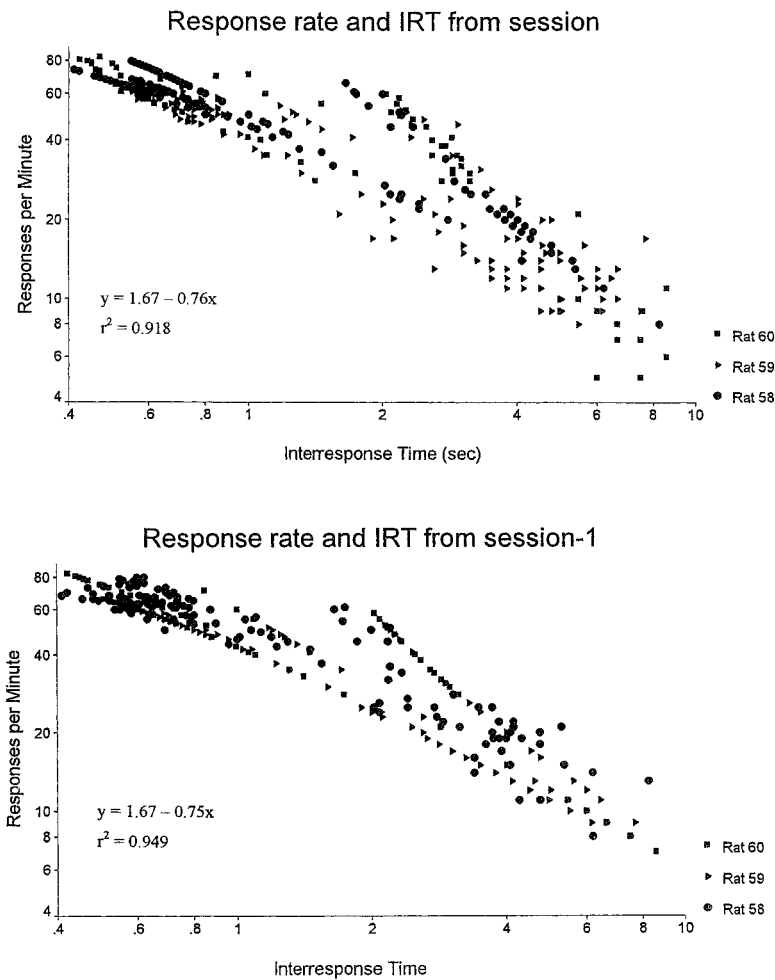


Fig. 2. Results from Experiment 1. Relation between response rate and mean reinforced IRT (in seconds, top panel), and between response rate and mean reinforced IRTs on the preceding session (bottom panel) for each rat, presented on a logarithmic scale. The regression of responses rate (y) on IRTs (x), and variance accounted (r^2), are also represented.

session of the study for all three rats. For 2 out of the 3 rats, the lagged correlation is significantly stronger than the correlation between the IRT and response rate within a session.

Taken together, these data replicate the results reported by Reed et al. (2000) using a within-subject design rather than the between-group design adopted in the latter experiment. These data from rat subjects, however, fail to replicate the results reported by McDowell and Wixted (1986) for human subjects that showed equivalent rates of responding on VR and VI+ schedules. One possibility why the rats failed to show such sensitivity

could be that they never responded quickly enough to experience the differential reinforcement of high rates of response on the VI+ schedule. Rates of response of the present rat subjects were lower than those of the human subjects in the study reported by McDowell and Wixted. This explanation is unlikely, however, because in both of the conditions in which a VI+ schedule was studied, the rats had previously been trained on a VR schedule with an equivalent feedback function and were responding at a high rate on that schedule. Despite starting VI+ training with a rate of response generated by a schedule with an equivalent feedback function, the

VI+ schedule failed to maintain the same level of responding.

The higher rate of responding on the VR schedule, relative to the appropriate VI+ comparison schedule, cannot be attributed to differences in the respective feedback functions of the contingencies, as this parameter was matched across the two schedules. The difference in levels of responding could be attributed, however, to any number of factors that did differ between the schedules. The rate of reinforcement was different between the schedules. This, however, might be attributed, in itself, to the failure of the rats to be sensitive to the molar properties of the VI+ schedule, as well as to their failure to respond quickly enough to earn reinforcers at a rate equivalent to the VR schedule. This possibility was taken up in the next experiment. Alternatively, it should be noted that the mean reinforced IRTs were much smaller for the VR schedules than the VI+ schedules. There was a very strong relation between the response rate on a session and the mean reinforced IRT on the preceding session. This lagged correlation begins to suggest a causal role for the differential reinforcement of IRTs. This finding is, nevertheless, still correlational in nature, but is consistent with a molecular interpretation of the results.

EXPERIMENT 2

Despite the failure of Experiment 1 to corroborate the findings of McDowell and Wixted (1986) with respect to the rates of response maintained on VR and VI+ schedules, these results do not mean that rats are not sensitive to the molar feedback properties of a VI+ schedule. It could be that both the molecular and molar features of a reinforcement schedule jointly determine behavior. If the differential reinforcement of IRTs is of prime importance in determining the behavior of nonhumans (see Peele *et al.*, 1984), then it may be that the reinforcement of shorter IRTs on a VR schedule, compared to a VI+ schedule, masks the effect of the molar feedback function. If this is true, then compared to a simple VI schedule that provides a similar rate of reinforcement and which reinforces similar IRTs, response rates would be higher on a VI+ schedule. Experiment 2 investigated this possibility.

METHOD

Subjects and Apparatus

Eight male Lister hooded rats served. Each was 8 to 9 months old at the start of training, had a free-feeding body-weight range of 520 to 600 g, and was maintained at 85% of this weight throughout the experiment. The rats had previously served in a study of stimulus preexposure effects in which they had seen lights and experienced the reinforcers to be used in the present study. They were, however, naive to lever pressing. The rats were maintained as described in Experiment 1. The apparatus was that described in Experiment 1.

Procedure

The rats were trained to lever press in five 15-min sessions with a CRF schedule in effect. After this training, the rats were divided into four pairs. During Phase 1, one of the rats in each pair received thirty 60-min sessions of a VI+ schedule with a feedback function equivalent to a VR 30. The second rat in each pair was yoked to the former rat such that a response made by the yoked VI rat was reinforced when a master rat in the VI+ group received reinforcement. During Phase 2, the master and yoked rat roles were reversed, such that the rat which had been the master VI+ rat now became the yoked VI rat, and vice versa for the other rat in each pair. There were thirty 60-min sessions of this training. All other experimental details were as described in Experiment 1.

RESULTS AND DISCUSSION

Inspection of the response rates displayed in Figure 3 reveals that during the last six sessions of each phase responding was reasonably stable for all rats. Also, there was no clear pattern of difference between the response rates engendered by each of the schedules. In Phase 1, for two of the pairs of rats (R61 and R62, and R67 and R68) response rate was higher in the VI+ schedule than on the corresponding VI schedule. In the remaining two pairs of rats, the rate of responding was higher for the VI schedule than for the VI+ schedule. Reversal of the contingencies during Phase 2 typically failed to reverse the response rates noted during Phase 1 (with the possible exceptions of Rats R65 and R66).

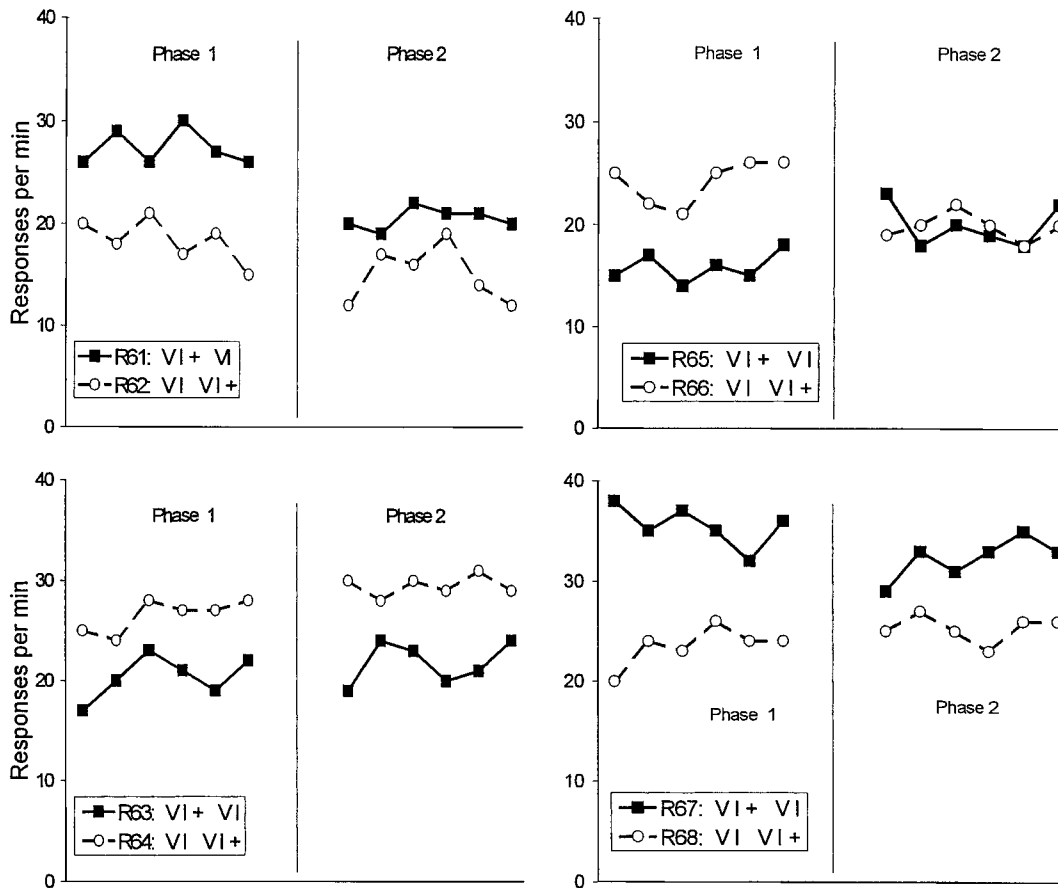


Fig. 3. Results from Experiment 2. Response rates for each of the four pairs of rats. VI+ = variable interval with an equivalent feedback function to a VR 30 schedule; VI = variable interval yoked to the VI+ schedule. The data are from the last six sessions of each phase.

These results demonstrate that rats' response rates were not sensitive to the molar feedback function generated by a VI+ schedule. There were no consistent differences between the rates of response produced on the VI+ schedule and those produced on the yoked VI schedule. That the response rates emitted by the two rats in each pair failed to reverse when the contingencies were reversed suggests that the response rate differences that did emerge between the schedules were not the result of the contingencies differentially affecting the different pairs of rats. Rather, the rate differences were probably a reflection of individual variations in free-operant response rates, and/or differences in the sensitivity of the individual rats to reinforcement on interval schedules.

Figure 4 displays the mean rates of rein-

forcement (top panel), and the mean reinforced IRTs (bottom panel), on both schedules for each rat. For all pairs of rats, in both phases of the experiment, the rates of reinforcement were similar to one another on each of the yoked schedules. It may be worthy of note that, although the difference was not great, the rate of reinforcement was usually lower on the yoked VI than on the VI+ schedule. This is not surprising given the adoption of a yoking procedure. The mean reinforced IRTs showed no systematic differences in both phases of the study for all pairs of rats.

These results present no evidence that would support the notion that rats are sensitive to the molar feedback function relating response rate to reinforcement rate. Rates of responding were just as high on the yoked VI

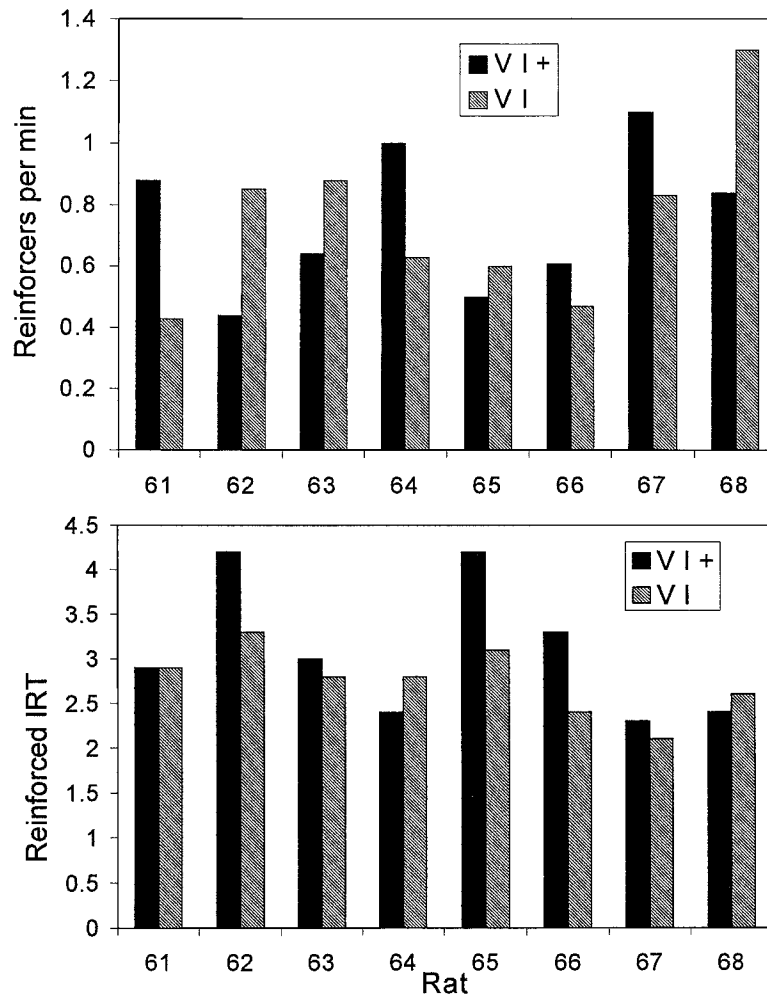


Fig. 4. Results from Experiment 2. Mean rates of reinforcement and mean reinforced IRT for all rats, over the last five sessions of each phase.

schedule as they were on the master VI+ schedule. Moreover, although there were some large differences in the mean reinforced IRTs between the schedules (e.g., compare R65 and R66 in Phase 1, and R61 and R62 in Phase 2), there were no systematic differences in this measure between the schedules. This was found even though the VI+ schedule (but not the VI schedule) has the capacity to differentially reinforce high rates of responding. It is unlikely that the levels of responding emitted by the rats prevented this function of the schedule from contacting behavior. By the end of each phase, rates of responding were as high as those seen in Experiment 1 when a VR versus

VI+ difference had emerged. Moreover, there was no difference in the performance of rats on the VI schedule and VI+ schedule when the rates were relatively high (see Rats R67 and R68) or relatively low (e.g., Rats R65 and R66). It might be noted that the mean reinforced IRTs produced by the two schedules also were similar to one another; a finding consistent with a molecular interpretation of the results.

EXPERIMENT 3

The results of Experiment 2 may have been the product of the use of a between-subjects yoking procedure. Church (1964) argued

that subjects may be differentially sensitive to response-contingent outcomes, and that such sensitivity may somehow influence response rates generated in master and yoked conditions. Certainly, it is clear that the rats employed as subjects in Experiment 2 did produce different rates of responding from one another, even when the rates of reinforcement that they experienced were matched. This could reflect differential sensitivity to the schedules employed.

Experiment 3 addressed this possibility by employing a within-subject yoking procedure. This procedure, in which each subject serves as its own control, equates the effect of the subject's sensitivity to response-contingent outcomes for both master and yoked-schedule conditions. The results cannot, therefore, be attributed to differential sensitivities to reinforcement between the master and yoked rats.

METHOD

Subjects and Apparatus

Three male Lister hooded rats served. Each was 13 to 14 months old at the start of training, had a free-feeding body-weight range of 495 to 620 g, and was maintained at 85% of this weight throughout the experiment. The rats had a similar history to those in Experiment 2 and were maintained as described in Experiment 1. The apparatus was that described in Experiment 1.

Procedure

The rats were trained to lever press on a multiple CRF CRF schedule. Each component of the schedule was programmed on a different lever and was signalled by a distinctive visual cue: either a constantly illuminated, or a flashing (100 ms on/100 ms off) jewel light, located above the corresponding response lever. The session began with the insertion of a lever into the chamber and the illumination of the associated visual stimulus. After 5 min, the lever retracted, the cue extinguished, and a 3-s intertrial interval (ITI) ensued before the other lever was inserted and its corresponding light was illuminated. Each session comprised eight 5-min components (each of the two components was presented four times during a session), and these components were presented in strict alterna-

tion. The rats then received four sessions of a multiple VI 30-s VI 30-s schedule. Each component was associated with a distinct visual cue and a separate lever, and the components were presented in strict alternation. Each component of the multiple VI 30-s VI 30-s terminated when the rat earned a food pellet, at which time the visual cue extinguished and the lever retracted. A 3-s ITI then ensued, followed by the insertion of the other lever and the illumination of its associated cue. Each session lasted until the rat had obtained 60 reinforcers (i.e., 30 in each component).

For the first critical phase of training, the rats responded on a multiple VI 60-s VI 60-s schedule. This schedule operated as described above for the multiple VI 30-s VI 30-s schedule. Phase 1 lasted for 20 sessions, and each session lasted until the rat had obtained 60 reinforcers (i.e., 30 reinforcers in each component). Each component ended when the rat had earned a food reinforcer. In Phase 2, a multiple VI+ VI y-s schedule was introduced for all rats. The VI+ schedule was programmed as described in Experiment 1 and had a feedback function corresponding to a VR 30 schedule. The requirement of the succeeding VI component was the same as that in the immediately preceding VI+ schedule component. This phase lasted for 20 sessions, and each session lasted until the rat obtained 60 reinforcers (i.e., 30 reinforcers in each component). Phase 3 consisted of a return to the baseline multiple VI 60-s VI 60-s schedule, and lasted for 20 sessions. Each session lasted until the rat obtained 60 reinforcers (i.e., 30 reinforcers in each component). Apart from the visual cues, the chamber was not illuminated.

RESULTS AND DISCUSSION

The rates of responding for all rats over the first and last five sessions of each phase are displayed in Figure 5. Inspection of these data shows that rates of responding were relatively, although not perfectly, stable at the end of each of the three phases for each rat. It is also clear that rates of responding were very similar in both components of the multiple VI 60-s VI 60-s schedule in Phase 1 for all 3 rats. These rates of responding were also recovered during the return to baseline in Phase 3. Rates of responding at the end of Phase 2 were lower than at the end of the

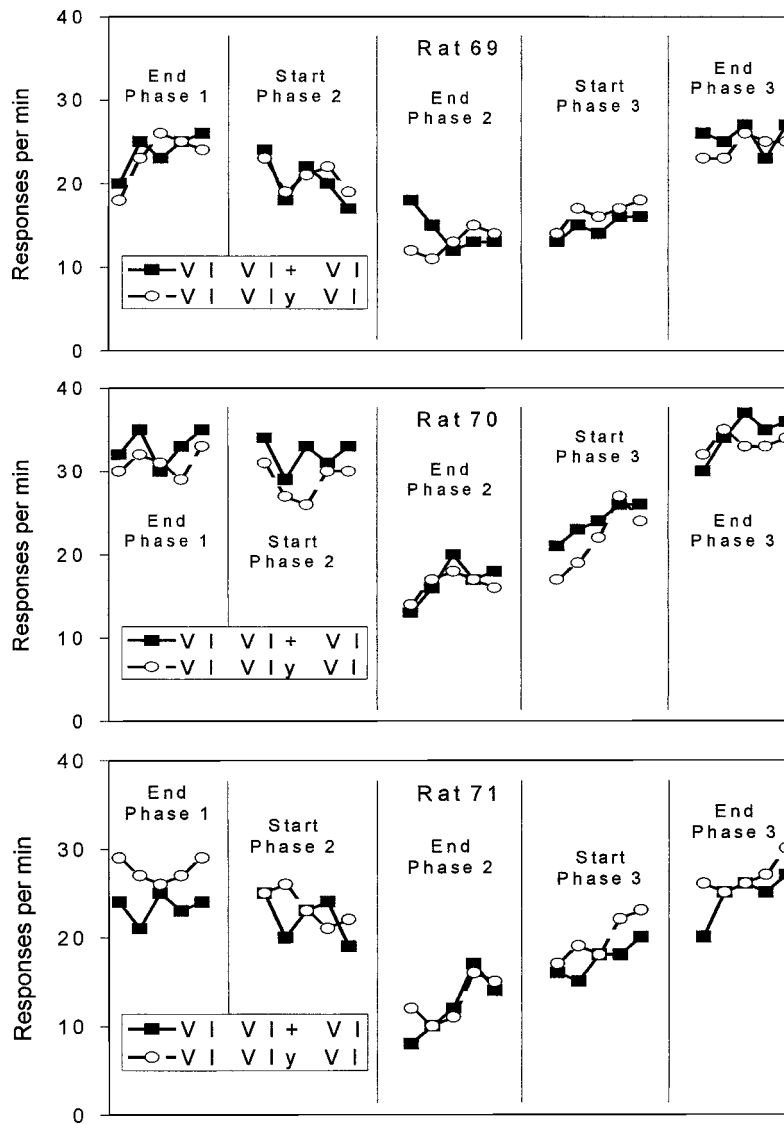


Fig. 5. Results from Experiment 3. Response rates over the first and last five sessions of each phase for each of the rats responding on a multiple VI+(30) VI y-s schedule. VI+ = variable interval with an equivalent feedback function to a VR 30 schedule; VI = variable interval yoked to the VI+ schedule.

other two phases. There was little difference, however, between the rates of response emitted to the two components of the multiple schedule across all phases.

The rates of reinforcement produced by particular rates of responding for both of the schedules employed during Phase 2 (VI+ vs. VI), for each rat, are displayed in Figure 6. Inspection of these feedback functions relating rates of reinforcement to rates of response shows that the function was different

on the two schedules. There was a linear function for the VI+(30) schedule, but this was not so evident for the VI schedule. On the latter schedule, once responding reached a particular level no further increases in reinforcement rate were produced. This suggests that the VI+ schedule was operating as programmed. Despite the different feedback function relating reinforcement to responding on the two schedules, however, the VI+ schedule did not produce substantially higher

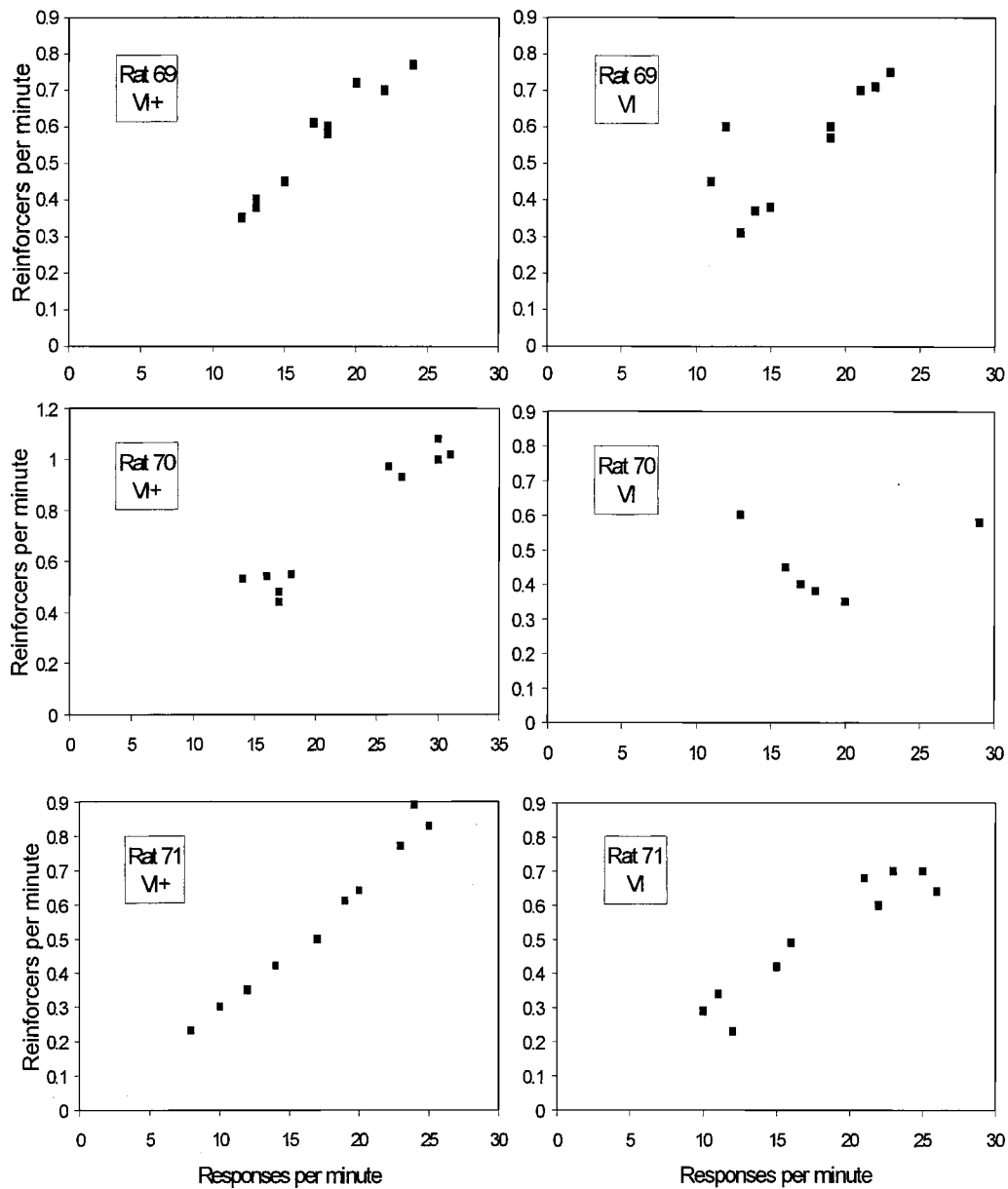


Fig. 6. Results from Experiment 3. Feedback function between response and reinforcement rate on both schedules for all 3 rats during Phase 2. Data are from the last 10 sessions of the Phase.

rates of responding than the VI schedule (see Figure 5).

Figure 7 displays the mean reinforcement rates (top panel) and the mean reinforced IRTs (bottom panel) for all 3 rats over all three phases of Experiment 3. The rates of reinforcement in both components of the multiple schedule were similar to one another for all 3 rats in all three phases of the study.

This is not surprising given that the schedules were identical in Phases 1 and 3, and that a yoking procedure was adopted in Phase 2. Rates of reinforcement were lower at the end of Phase 2 than in the other two phases of the study.

The mean reinforced IRTs generally were similar in both components of the multiple schedule in all three phases of the study for

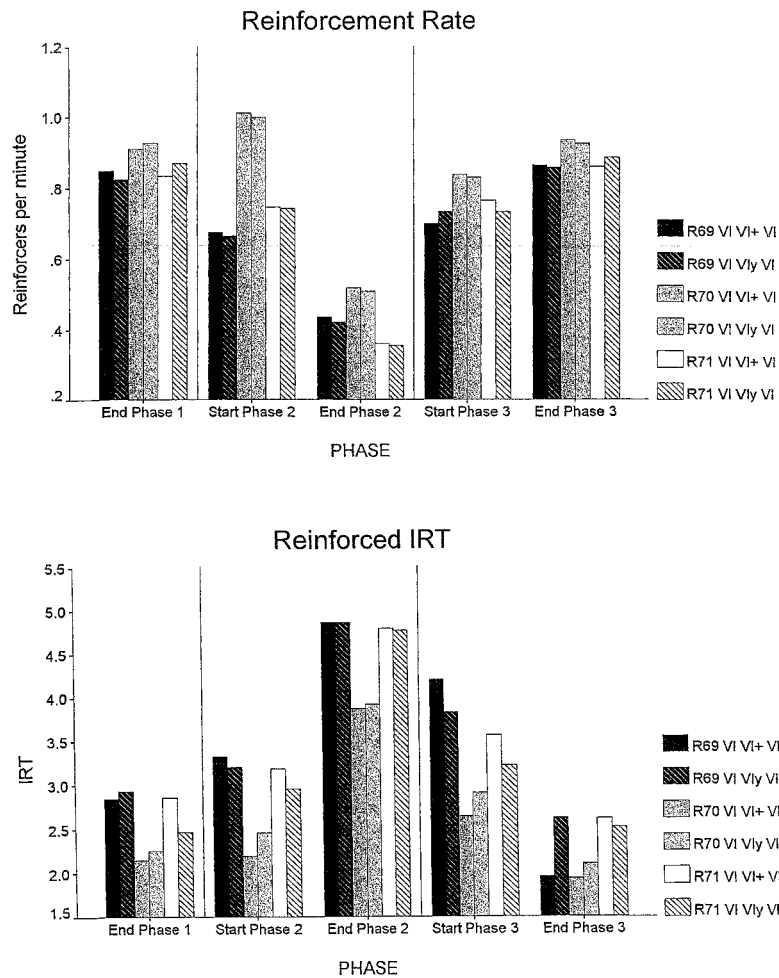


Fig. 7. Results from Experiment 3. Mean rates of reinforcement and mean reinforced IRT for all rats over the first and last five sessions of each phase.

all 3 rats. These mean reinforced IRT values were longer for each rat by the end of Phase 2 than in the first and third phase.

Taken together, the results from Experiment 3 corroborate the suggestion that rats do not appear to be sensitive to the molar feedback function properties of a VI+ schedule. There was no systematic difference between rates of responding on the VI+ and yoked VI schedules. This replicates the results reported in Experiment 2, but using a within-subject yoking procedure rather than a between-subject procedure. The use of a within-subject procedure overcomes the possibility that the results of Experiment 2 reflected differential sensitivities of the master and yoked rats to reinforcement (see Church, 1964). Al-

though it cannot be the case that the results are due to differences between rats in their sensitivities to reinforcement, it may be the case that rats display altered sensitivities during a session. This suggestion is not a likely explanation given that the components of the multiple schedule were experienced across the session and that baseline performance was largely recovered.

One note of caution should be sounded, however, regarding these results. It is apparent that response rates did not differ much between the components. This could indicate that both elements of the multiple schedule were controlling rate to the same degree. It could also indicate, however, that there was a lack of discrimination between the compo-

nents used. This is particularly an issue because reinforcer-terminated components may produce less discrimination than time-based components. In a component with a lower rate of reinforcement, a rat may respond more quickly than otherwise because the change of component to a richer schedule is itself reinforcing, thus contaminating the response rate data. Although this remains a possibility, it should be noted that the same procedure has been used elsewhere to test schedule differences and has been shown to produce good discrimination between components (see Reed, 1991).

A further issue concerns the presentation of the components in strict alternation. This procedure may have introduced the possibility for contrast effects to exert an influence. This is made less likely, however, by the use of schedules with equated rates of reinforcement and by the adoption of a relatively long (3-s) intercomponent interval.

GENERAL DISCUSSION

The preceding experiments have demonstrated that rats' rates of responding were not sensitive to a linear feedback loop relating response rate to reinforcement rate on a VI schedule. These results bear on two issues regarding schedule-controlled behavior. First, it is clear that, at least within the parameters studied in the present experiment, the feedback function relating response rate to reinforcement rate did not exert an influence on rats' overall levels of responding. Response rates were much lower on a VI+ schedule than on the corresponding VR schedule (Experiment 1). Similarly, response rates were no different on a VI+ schedule than on a VI schedule matched in terms of rate of reinforcement (Experiments 2 and 3). Taken together, these results show that levels of performance are lower on a VI+ schedule than on a VR schedule with an equivalent feedback function, and that levels of performance essentially are equivalent on a VI+ schedule and a VI schedule with a "weaker" function between response rate and reinforcement rate. These results are consistent with the data from the studies reported by Cole (1999) and Reed et al. (2000), and are at odds with those reported by McDowell and Wixted (1986).

Although the VI+ and VI schedules produced the same levels of responding, one aspect of the present results is worth comment as it may point to a difference between these schedules. Responding sometimes ceased on the VI+ schedule, but not under the VI schedule. This result was also obtained in some VI+ schedule conditions by Cole (1999). Given that reinforcement probability increases with the passage of time on a VI+ schedule, it might be expected that these schedules would share the "rejuvenating" effect characteristic of VI schedules. That is, "strained" performance would not be expected as readily on VI+ schedules as it is on VR schedules, especially because the overall response rates on the former schedule are closely similar to the rates on a yoked VI schedule. This may point to some difference between the VI+ and VI schedules not reflected in response rate per se, and may indicate some form of differential sensitivity to the two schedules.

In contrast to the above evidence that suggests rats are not sensitive to the response rate/reinforcement rate feedback function, the results from these experiments suggest that when reinforced IRTs are similar to one another, response rates will also be similar to one another. This molecular interpretation of the pattern of responding maintained on the VI+ schedule, however, should be not be adopted without some qualification, at least concerning the manner in which differential reinforcement of IRTs exerts an influence over response rates. In Experiment 3, the distribution of reinforced IRTs (as well as the mean) was examined on a VI+ schedule and on a VI schedule with an equivalent rate of reinforcement. Both schedules tended to reinforce longer IRTs than had been reinforced on VR schedules (see Experiment 1). Additionally, the mean reinforced IRTs on the VI+ and simple VI schedules were very similar. However, there was more variation in the IRTs that were reinforced on the VI+ schedule compared to the VI schedule (Experiment 3). It is unclear whether this bigger variation in reinforced IRTs signifies anything in particular. Certainly, it appears that it exerts little effect on the overall response rate. However, when subjects have shown apparent sensitivity to the feedback functions of schedules, differences in the patterns of reinforced IRTs

have also been revealed (see Reed & Schachtman, 1991). It could be that the variation in reinforced IRTs may be exerting some influence on performance not reflected in the measures taken in this series of experiments.

The second implication to be drawn from these data is that whatever was controlling performance in the human subjects studied by McDowell and Wixted (1986) was not operating to control performance in the non-human subjects used in the present experiments. This may reflect a species difference in the schedule parameters to which humans and nonhumans are sensitive. It may be that humans are sensitive to the overall characteristics of the schedule, whereas nonhumans are not sensitive to these factors. Alternatively, it may be that human behavior does not come under schedule control in the same way as does nonhuman behavior. Several studies have shown that human performance on certain schedules of reinforcement is more rule governed than contingency shaped (e.g., Mathews, Shimoff, Catania, & Sagvolden, 1977). It may be that such rule-governed behavior was manifest by the subjects in the study reported by McDowell and Wixted, although other than their subjects being human, there is little additional evidence to suggest that such rule-governed behavior did occur.

Even if the behavior were not rule governed, there may be reasons to suggest that human behavior does not always come under schedule control. In a series of studies (Reed, 1994, 1999) it has been shown that human response rates appear to follow those that would typically be expected on the basis of results from nonhumans if the response emitted by the human subjects is associated with some nontrivial cost. At low levels of response cost, it may be either that responding is always at asymptote for humans, or that the response cannot be compared to that emitted by a nonhuman in a conditioning chamber. To reduce the argument to the extreme, if there is no noticeable cost in emitting the response, then there cannot be a noticeable response to come under reinforcement control. This last suggestion appears unlikely in the case of McDowell and Wixted (1986) as they report a response force requirement of 120 N. This would appear to represent costly responding for human subjects, especially when some of the subjects were responding at two

responses per second! (Of course, the issue of what represents costly responding is an empirical one and cannot be addressed satisfactorily in such an a priori manner.)

It may well be the case that circumstances that promote sustained responding would allow rats to contact these molar properties of the VI+ schedule. Aspects of the situation, such as the rats' level of motivation or the length of time spent pausing, may impact behavior. One possibility concerns the type of reinforcer that is employed. Reinforcers that require a consummatory response may affect performance on the VI+ schedule by reducing behavior and reducing the rate at which reinforcement is scheduled. In the experiments where sensitivity to the molar feedback function has been demonstrated, there usually is no consummatory responding. In these studies responding can continue at largely uninterrupted rates, keeping rates of reinforcement high. Manipulations that maintain rats' responding at a high rate may also allow sensitivity to the molar contingencies to be maintained.

Any of these suggestions appear to warrant further investigation, but it would be unwise to speculate further on the basis of the present data. The present studies have not found any evidence of sensitivity to this particular feedback function. To this extent, they support the molecular view of response learning. However, both molecular and molar contingencies are aspects of the environment that could come to control behavior. It is possible that these aspects come to control behavior under different circumstances.

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ERRATUM

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The Appendix on page 20 should be replaced by the following:

APPENDIX

For each pigeon, values of a , $\log c$, and r^2 for the indicated periods of each trial during each condition.

		576			582			604		
		1st half	2nd half	Full	1st half	2nd half	Full	1st half	2nd half	Full
Baseline	$a =$	0.411	0.134	0.401	0.796	0.185	0.858	0.434	0.281	0.352
	$\log c =$	0.040	-0.171	0.003	-0.029	-0.227	-0.086	-0.036	-0.099	-0.030
	$r^2 =$	0.490	0.749	0.787	0.543	0.984	0.737	0.340	0.901	0.911
Reversal	$a =$	0.284	0.316	0.450	1.548	0.229	0.330	0.778	0.212	0.443
	$\log c =$	-0.037	0.226	0.114	0.577	0.173	0.104	0.018	0.157	0.004
	$r^2 =$	0.250	0.842	0.807	0.756	0.953	0.830	0.930	0.953	0.782
Clock	$a =$	0.570	0.631	0.779	0.734	0.736	0.837	1.089	1.325	0.621
	$\log c =$	-0.275	0.139	-0.017	-0.189	0.056	-0.035	0.178	-0.260	-0.058
	$r^2 =$	0.898	0.950	0.928	0.844	0.837	0.931	0.888	1.000	0.799
Baseline	$a =$	0.247	0.440	0.581	0.151	0.238	0.315	0.222	0.488	0.503
	$\log c =$	0.384	-0.057	0.083	0.106	-0.117	-0.037	0.108	-0.176	-0.101
	$r^2 =$	0.317	0.751	0.821	1.000	0.743	0.829	1.000	0.847	0.757
Assigned	$a =$	0.389	0.296	0.472	0.771	0.194	0.723	0.809	0.449	0.746
	$\log c =$	0.131	0.403	0.184	0.101	0.502	0.089	0.057	0.327	0.041
	$r^2 =$	0.802	0.589	0.796	0.895	0.227	0.940	0.822	0.888	0.929
RI	$a =$	1.334	1.183	0.875	1.207	0.331	0.825	0.851	6.269	0.777
	$\log c =$	-0.378	0.217	-0.106	-0.689	-0.306	-0.198	-0.013	3.960	0.006
	$r^2 =$	0.932	0.996	0.951	0.902	0.790	0.917	1.000	1.000	0.953
Reversal	$a =$	0.414	-2.349	0.644	0.582	-1.245	0.626	0.549	1.746	0.701
	$\log c =$	-0.074	3.890	0.040	0.130	1.581	0.165	-0.017	-0.869	0.109
	$r^2 =$	1.000	1.000	0.939	0.909	1.000	0.929	0.849	1.000	0.936
		605			613			614		
		1st half	2nd half	Full	1st half	2nd half	Full	1st half	2nd half	Full
Baseline	$a =$	-3.623	0.277	0.388	0.227	0.144	0.193	0.648	0.519	0.542
	$\log c =$	0.951	-0.206	-0.112	0.061	-0.010	0.039	-0.143	-0.088	-0.077
	$r^2 =$	1.000	0.834	0.589	1.000	0.714	0.860	1.000	0.712	0.943
Reversal	$a =$	0.917	0.309	0.458	1.184	0.249	0.898	0.668	0.051	0.342
	$\log c =$	0.300	0.085	0.005	0.210	0.313	0.089	0.103	0.114	-0.073
	$r^2 =$	0.502	0.438	0.737	0.929	0.874	0.839	0.646	0.090	0.694
Clock	$a =$	0.951	0.977	0.997	0.000	0.536	0.585	0.812	0.659	0.496
	$\log c =$	-0.012	0.026	0.008	0.000	0.183	0.133	0.072	-0.267	-0.143
	$r^2 =$	1.000	0.991	0.997	0.000	0.866	0.859	1.000	0.385	0.691
Baseline	$a =$	0.804	0.349	0.475	0.965	0.289	0.519	0.478	0.325	0.429
	$\log c =$	-0.133	-0.104	-0.001	-0.148	0.029	0.185	-0.330	-0.389	-0.313
	$r^2 =$	0.988	0.937	0.941	0.818	0.949	0.835	0.898	0.590	0.903
Assigned	$a =$	0.453	-3.575	0.585	0.888	0.815	0.734	0.811	0.094	0.437
	$\log c =$	0.033	5.357	0.075	-0.078	-0.240	-0.107	0.150	0.214	0.086
	$r^2 =$	0.962	1.000	0.893	0.959	0.618	0.929	0.911	0.543	0.679
RI	$a =$	6.304	1.175	1.160	0.863	0.788	0.614	0.580	1.072	0.656
	$\log c =$	-0.189	0.050	0.028	-0.419	0.108	-0.120	-0.149	0.232	-0.159
	$r^2 =$	1.000	1.000	0.888	0.797	1.000	0.877	0.995	1.000	0.937
Reversal	$a =$	0.443	0.000	0.759	0.712	0.579	0.734	0.773	0.470	0.678
	$\log c =$	0.131	0.000	0.254	-0.008	0.053	0.022	0.026	0.188	0.002
	$r^2 =$	1.000	0.000	0.905	0.808	1.000	0.907	0.938	0.442	0.910