*RESPONSE-RATE DIFFERENCES IN VARIABLE-INTERVAL
AND VARIABLE-RATIO SCHEDULES:
AN OLD PROBLEM REVISITED*

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In Experiment 1, a variable-ratio 10 schedule became, successively, a variable-interval schedule with only the minimum interreinforcement intervals yoked to the variable ratio, or a variable-interval schedule with both interreinforcement intervals and reinforced interresponse times yoked to the variable ratio. Response rates in the variable-interval schedule with both interreinforcement interval and reinforced interresponse time yoking fell between the higher rates maintained by the variable-ratio schedule and the lower rates maintained by the variable-interval schedule with only interreinforcement interval yoking. In Experiment 2, a tandem variable-interval 15-s variable-ratio 5 schedule became a yoked tandem variable-ratio 5 variable-interval x -s schedule, and a tandem variable-interval 30-s variable-ratio 10 schedule became a yoked tandem variable-ratio 10 variable-interval x -s schedule. In the yoked tandem schedules, the minimum interreinforcement intervals in the variable-interval components were those that equated overall interreinforcement times in the two phases. Response rates did not decline in the yoked schedules even when the reinforced interresponse times became longer. Experiment 1 suggests that both reinforced interresponse times and response rate–reinforcement rate correlations determine response-rate differences in variable-ratio 10 and yoked variable-interval schedules in rats. Experiment 2 suggests a minimal role for the reinforced interresponse time in determining response rates on tandem variable-interval 30-s variable-ratio 10 and yoked tandem variable-ratio 10 variable-interval x -s schedules in rats.

Key words: variable-ratio schedule, variable-interval schedule, tandem schedule, yoked schedule, reinforced interresponse time, response rate–reinforcement rate correlation, molar feedback function, lever press, rats

It has been observed repeatedly that when the overall rates and patterns of reinforcement are equated on variable-interval (VI) and variable-ratio (VR) schedules, VR schedules generate higher response rates than VI schedules do (Catania, Matthews, Silverman, & Yohalem, 1977; Ferster & Skinner, 1957; Reed, Schachtman, & Hall, 1988; Skinner, 1938; Zuriff, 1970). Two quite different explanations have been provided to account for this difference. Some writers (e.g., Anger, 1956; Platt, 1979; Shimp, 1969) have suggested that, assuming there is variability in interresponse times (IRTs), lower response rates might come

to predominate on VI schedules because VI schedules tend to reinforce long IRTs. On the other hand, a number of writers (cf. Baum, 1973, 1981; Rachlin, 1978; Rachlin & Burkhard, 1978; Staddon, 1979) have suggested that VR schedules lead to relatively higher response rates than VI schedules do because on VR schedules there is a direct correlation between rate of responding and rate of reinforcement, whereas on VI schedules there is little relationship between rate of responding and rate of reinforcement except at very low response rates. The claim is that organisms are sensitive to such molar feedback and respond accordingly—at a high rate on VR schedules and at a lower rate on VI schedules.

There has been considerable research on the relative contributions of these different but not fundamentally incompatible principles in determining response rate on various schedules. There is evidence that the reinforced IRT plays a major role in schedules resembling VI (e.g., Galbicka & Platt, 1986; Shimp, 1973). There is also a good deal of evidence that animals are not sensitive to molar feedback in complex linear VI schedules in which there is a negative correlation between rate of response and rate

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of reinforcement (e.g., Ettinger, Reid, & Stadon, 1987; Vaughan & Miller, 1984) or in interlocking FR schedules in which there is a negative correlation between the size of the FR and response rate (Ettinger et al., 1987). Finally, there is also evidence that in schedules in which the degree of correlation between response rate and reinforcement rate is varied and duration of IRT is controlled, the response rate–reinforcement rate correlation exerts considerable control over behavior (Dawson & Dickinson, 1990; McDowell & Wixted, 1986).

The role of the reinforced IRT was compared explicitly in simple VI and VR schedules in a study by Peele, Casey, and Silberberg (1984). These researchers examined the role of the reinforced IRT in VI and VR schedules by testing pigeons on a multiple VR 200 yoked VI schedule and manipulating the duration of the reinforced IRT in the VI component. Specifically, in the first of several experiments, they used the interreinforcement intervals (IRIs) generated in the VR 200 component to program the minimum-required IRIs in the VI component. In the first phase, the second component was a simple yoked VI, whereas in the second phase, the VI reinforcer was delivered only after the expiration of the required IRI *and* after the emission of an IRT that belonged to the same quartile as those emitted in the VR component. They reported that the differences in response rate between the VR and VI components seen in the first phase were eliminated in the second phase following imposition of the short IRT requirement. They failed to point out, however, that in 3 of the 4 birds, the elimination of this response-rate difference was due not so much to an increase in the VI response rate as to a decrease in the VR response rate. That is, the response-rate change was more prevalent in the unaltered than in the altered component of the multiple schedule. It has been shown that when manipulations are made to the reinforcement rate (Reynolds, 1961), or response rate (Terrace, 1966) in one component of a multiple schedule, there is often a change in the response rate seen in the other unaltered component. Although the manipulation made by Peele et al. involved alterations to the duration of the reinforced IRT rather than to reinforcement rate, the potential for schedule interactions in that situation is, at best, unknown. The data reported by Peele et al. sug-

gest that such an interaction may have occurred and this precludes unequivocal interpretation of the data. The present Experiment 1 was similar to the first experiment of Peele et al. but reduced the potential for schedule interaction by eliminating the within-session yoking of VR and VI.

EXPERIMENT 1

METHOD

Subjects

Four hooded rats of the Long-Evans strain were maintained at 80% of their ad lib weights by means of a food-restrictive diet but with unlimited access to water. The rats were experimentally naive and were housed in individual cages. The treatment of all animals was in accordance with the guidelines of the Canadian Council on Animal Care.

Apparatus

A standard Gerbrands operant chamber (29 cm by 23 cm by 19 cm high) was used. The chamber had two levers, mounted on either side of the feeder wall, their centers 8.5 cm above the floor and 11.5 cm from the left and right side walls, respectively. Only the left lever, which required a force of about 0.44 N to depress completely, was operable, the right lever having been immobilized. The feeder was centered on the feeder wall just above the floor and could be reached through an opening (2.5 cm wide by 3.0 cm). The cuelight was located 14 cm above the floor and directly over the feeder opening. The cuelight remained on during all the experimental procedures reported here, except during pellet deliveries (when it was off for approximately 0.25 s). A Commodore® 64 computer was used to program events in the chamber and to record relevant data.

Procedure

Phase 1. Shaping was employed to establish a lever-pressing response to the left lever, after which 20 food reinforcers were delivered on a continuous reinforcement schedule. Following this, the schedule of food reinforcement was established as VR 5 for one session and VR 10 thereafter. The 10 different ratios making up the VR 10 were those used by Zuriff (1970); a daily session consisted of four cycles through

the ratios, using a different random starting point for each session, for a total of 40 reinforcements. During each daily session, overall response rates and local response rates (those whose calculation was based on the time from the first response until the reinforced response in a ratio involving at least two responses) were recorded. In addition, the 40 IRIs for each rat during each daily session and the 40 reinforced IRTs (the time between the reinforced response and the penultimate response in ratios involving at least two responses; this time was 0 when the ratio was 1) were recorded and stored on a computer disk for use in the yoked sessions to follow. Daily sessions were continued for 60 sessions, at which point a visual inspection of the local response rates suggested that during Sessions 41 through 60 a between-session baseline had been established.

Phase 2. Rats 2 and 4 were placed on a VI schedule in which the minimum-required IRIs were those produced earlier during Sessions 41 through 60 on VR 10 (IRI yoke). In each of the 20 sessions of Phase 2, the 40 minimum-required VI intervals were equal to the 40 IRIs actually generated by the rat during the corresponding VR 10 session recorded earlier. Following the passage of each such minimum-required VI interval, the next lever press produced a food pellet. Rats 1 and 3 were placed on a VI schedule for 20 sessions in which not only the minimum IRIs but also the reinforced IRTs were yoked to the corresponding Sessions 41 through 60 of VR 10 (IRI+IRT yoke). At the start of each session of the IRI+IRT yoke for each rat, not only the IRIs from the corresponding VR 10 session but also the reinforced IRTs from that session were read from the disk. Moreover, the reinforced IRTs were sorted by duration from shortest to longest, and the upper limit of the first three quartiles was determined. Following the passage of each required interreinforcement interval in the IRI+IRT yoke, the quartile of the corresponding VR 10 reinforced IRT was determined, and the rat was required to emit an IRT at least as short as the upper limit of that quartile. In the case of the upper quartile, any IRT was accepted for delivery of a food pellet. Following the procedure of Peele et al. (1984), the intention in using the upper limit of the quartile containing the VR 10 reinforced IRT instead of simply the value of the VR 10 reinforced IRT itself was to produce a distri-

bution of VI reinforced IRTs whose median duration would be about equal to the median duration of the VR 10 reinforced IRTs from that session. Within the IRI+IRT yoke, failure to satisfy the minimum IRT requirement after 100 lever presses resulted in cancellation of that reinforcer and inauguration of the next required interfood interval. Overall and local response rates were calculated only from data obtained from cycles terminating in reinforcement and were recorded for each rat during each session.

Phase 3. In Phase 3, Rats 2 and 4 were switched to the IRI+IRT yoke and Rats 1 and 3 were switched to the IRI yoke for an additional 20 sessions of yoked VI. During these sessions, the IRIs and reinforced IRTs were yoked back to the same Phase 1 VR 10 sessions used in the Phase 2 yokes, and both overall and local response rates were calculated and recorded for each rat during each session.

Phase 4. In Phase 4, all 4 rats were returned to a VR 10 schedule for an additional 20 sessions, and overall and local response rates calculated as in Phase 1.

RESULTS

The principal findings of Experiment 1 are presented in Figure 1. The data from Rat 4 are not presented, because Rat 4 failed to meet the minimum reinforced IRT in Phase 3 on many occasions. Rats 1 and 3 obtained all 40 scheduled reinforcers in the IRI+IRT yoke, and Rat 2 obtained almost all the scheduled IRI+IRT yoke reinforcers (median = 40), but Rat 4 obtained less than 80% of the scheduled IRI+IRT yoke reinforcers (median = 34). The line graphs on the left show the sessional local response rates in each of the four phases, and the bar graphs on the right show the phase means for the same data. The data show that for Rat 2, which was shifted directly to the IRI yoke, the response rate fell immediately, and although it rose somewhat, it failed to recover completely to the VR 10 level when the IRT restriction was imposed. The data for Rat 3 are similar to those from Rat 2, with the local response rate for the IRI+IRT yoke midway between that for VR and the IRI yoke. The data from Rat 1, however, are more equivocal, with variability compromising the observation that both the IRI and the IRI+IRT yokes produced response rates lower than those observed in VR 10. Recovery of VR 10 re-

Fig. 1. Local response rates in Experiment 1 as a function of reinforcement schedule: (a) VR 10, (b) IRI-yoked VI, (c) IRI+IRT-yoked VI, and (d) VR 10. Sessional data are presented on the left, and phase means are presented on the right. The standard error of the mean is represented by a vertical line on each bar.

sponse rates occurred in Phase 4 for all 3 rats; it should be noted that there was no yoking to this phase. Local response rates rather than overall response rates were chosen for presentation in Figure 1 because the local response-rate data are slightly less variable. As Table 1 shows, however, the same effects occurred when overall response rates are compared across phases.

The phase means for the median reinforced IRTs and the interfood times are presented in Figure 2. The IRI+IRT yoke had the desired effect, with the phase means of the median sessional reinforced IRTs no longer than those observed in VR 10 and much shorter than those observed in the IRI yoke (except for Rat 1, for which it is merely shorter). Although the imposition of the IRI+IRT yoke led to a slightly greater delay of reinforcement over that observed in the IRI yoke, this difference was probably not significant, given the standard errors of the means (Figure 2, right). In addition, slightly shorter mean interfood times occurred in VR than in either yoked condition. In particular, for all 3 rats there was a decrease in mean interfood time in Phase 4. Again, however, these differences are small relative to the standard error of the mean, except for Rat 2.

DISCUSSION

The results of Experiment 1 suggest a role for both the reinforced IRT and the correlation between rate of responding and rate of reinforcement. For Rats 2 and 3, although the effect of requiring short IRTs was to generate higher response rates in the IRI+IRT yoke than in the IRI yoke, the response rate failed to attain the level that had been maintained by VR 10. For Rat 1, the response rate in the IRI+IRT yoke was not increased relative to that observed in the IRI yoke, with both rates being lower than the response rates observed in VR 10, but none of these differences was large relative to the variability in the data. On the one hand, the IRT restriction seemed to be incapable of raising back to VR 10 levels a response rate already lowered by a yoked VI schedule (Rat 2). On the other hand, the IRT restriction had some effect in that it attenuated the lowering of VI response rates relative to those observed when there was no restriction on the reinforced IRT (Rat 3). The mean IRT data make it clear that the effects seen in Phases 2 and 3 were not due to delay of reinforcement resulting from the imposition of the IRT restriction.

These results suggest that the data reported by Peele et al. (1984) may have underestimated the contribution of the response rate–reinforcement rate correlation, inherent in VR but not VI schedules, to the response-rate differences often seen in VR and yoked VI schedules. Although it is tempting to conclude that this is due to the absence of schedule interactions in the present research, it must be noted that differences in the schedule parameters (VR 10 instead of VR 200) and species (rats instead of pigeons) may also be factors. Both Ferster and Skinner (1957) and Morse (1966) have noted that the effects of schedules on behavior are very dependent on the parameters of those schedules. Also, several writers have noted that not only choice of species but also choice of operant response can have profound effects on behavior (cf. Cole, 1983; Schwartz & Gamzu, 1977).

EXPERIMENT 2

Peele et al. (1984) attempted to answer the question of what causes VI VR response-rate differences in a different way in another experiment. Again they used a multiple schedule, but this time one it was in which the components were not simple VR and VI schedules but rather tandem VR VI and tandem VI VR schedules. In these tandem schedules, reinforcement followed completion of the requirements of the second component in the tandem sequence, with no exteroceptive stimulus marking the passage from the first to the second component. In their multiple tandem VR 200 VI tandem VI VR 200 schedule, the times taken to complete the VR ratios in each tandem component provided the minimum IRIs in the VI schedule of the other tandem component. By this means, the interreinforcement times in each multiple component were always guaranteed to be equal, thus equating the molar feedback functions in the two multiple components. Because one multiple component ended in VR, however, and the other ended in VI, this provided an arrangement in which there should have been natural variation in the duration of the reinforced IRT in the VR and VI components, with that in the VI being longer. The hypothesis was that if the duration of the reinforced IRT is a factor governing response rate on VR and VI schedules, then

Table 1
Phase averages from Experiment 1. Standard errors of the mean appear in parentheses.

Rat	Schedule	Overall response rate (resp/min)	Local response rate (resp/min)	Median reinforced IRT (s)	Mean interfood time (s)
2	VR	70.2 (19.6)	109.4 (9.1)	0.21 (0.01)	8.5 (2.9)
	IRI	53.9 (13.1)	76.4 (13.1)	0.91 (0.42)	10.1 (3.1)
	IRI + IRT	62.7 (12.2)	86.2 (7.0)	0.25 (0.02)	12.4 (3.8)
	VR	85.2 (13.8)	112.3 (7.9)	0.27 (0.02)	6.7 (1.9)
	VR	74.9 (29.9)	132.7 (17.2)	0.20 (0.01)	8.7 (4.2)
	IRI + IRT	69.1 (22.8)	117.2 (16.3)	0.21 (0.11)	12.9 (6.4)
	IRI	65.8 (23.9)	110.9 (19.1)	0.31 (0.06)	10.8 (5.0)
	VR	84.7 (37.3)	139.62 (17.0)	0.18 (0.02)	8.4 (5.0)
3	VR	70.6 (20.5)	111.2 (16.5)	0.21 (0.01)	8.4 (2.7)
	IRI + IRT	68.4 (20.4)	95.7 (10.3)	0.21 (0.07)	12.4 (4.7)
	IRI	58.6 (16.2)	77.9 (11.4)	0.81 (0.24)	9.9 (3.1)
	VR	95.1 (19.9)	120.7 (14.4)	0.21 (0.06)	6.2 (2.8)

the tandem VI VR component should lead to higher response rates than does the tandem VR VI component. The results for 3 of 4 birds supported this view, with the tandem component ending in VR yielding higher response rates than the tandem component ending in VI. The present Experiment 2 was similar to that reported by Peele et al. but used rats instead of pigeons, used denser reinforcement schedules, and was designed to avoid the potential for schedule interaction inherent in within-session yoking.

METHOD

Subjects and Apparatus

Four hooded rats of the Long-Evans strain were used in the present experiment. All had been used in a pilot study involving tandem VR VI and tandem VI VR schedules. As in the previous experiment, they were deprived to 80% of their ad lib weights, given free access

Fig. 2. The left column shows mean median reinforced IRTs in Experiment 1 as a function of reinforcement schedule: (a) VR 10, (b) IRI-yoked VI, (c) IRI+IRT-yoked VI, and (d) VR 10. The right column shows mean interfood time in Experiment 1 as a function of reinforcement schedule: (a) VR 10, (b) IRI-yoked VI, (c) IRI+IRT-yoked VI, and (d) VR 10. When large enough to warrant graphing, the standard error of the mean is represented by a vertical line on each bar.

to water, housed in individual cages, and treated in accordance with the guidelines established by the Canadian Council on Animal Care.

The same apparatus used in the first experiment was employed in the present experiment.

Procedure

Phase 1. Rats 5 and 6 were placed on a tandem VI 15-s VR 5 schedule, and Rats 7 and 8 were placed on a tandem VI 30-s VR 10 schedule in which nonsignaled entry into the VR component was provided by the first lever press to follow expiration of the minimum IRI in the VI component, and in which reinforcement followed fulfillment of the ratio in the VR component. The VI intervals were adapted from those provided by Catania and Reynolds (1968) so as to yield 10 instead of 15 intervals, and the 10 VR ratios were those

provided by Zuriff (1970). The largest VR ratio was paired with the longest VI interval, the second largest VR ratio with the second longest VI interval, and so on. Daily sessions consisted of 30 cycles through the tandem components, using a different random starting point in each session, and resulting in 30 reinforcers per session. During each daily session, overall response rates were recorded. Because of the compound nature of the schedule, local response rates were not recorded. In addition, the 30 overall interreinforcement times from each daily session were recorded and stored on disk for use in the subsequent yoked sessions. Training continued for 80 sessions; visual inspection of the overall response rates suggested that the last 20 sessions constituted a baseline.

Phase 2. In Phase 2, the rats were shifted to a tandem VR VI schedule yoked to the schedule used in Phase 1. In these tandem

Fig. 3. Response rates in Experiment 2 as a function of reinforcement schedule: (a) tandem VI VR, (b) yoked tandem VR VI, and (c) tandem VI VR. Sessional data are presented on the left, phase means are presented on the right. The schedule designations beneath the phase mean bars refer to the final component in the tandem schedule. The standard error of the mean is represented by a vertical line on each bar.

schedules, the VR component was the same one used in Phase 1, but it formed the first component of the tandem schedule in this phase. The VI component was one in which the minimum IRIs were equal to the overall inter-reinforcement times from the corresponding Phase 1 cycle, minus the time just taken to complete the VR component in the current Phase 2 cycle. Training continued for 20 sessions, yoked to the last 20 Phase 1 sessions with overall response rates being recorded. This arrangement guaranteed that the overall interreinforcement times in Phase 1 and Phase 2 were equivalent on a rat-by-rat, reinforcer-by-reinforcer, and session-by-session basis.

Phase 3. In Phase 3, the rats were returned to the original tandem schedules used in Phase 1 for an additional 20 sessions, during which time overall response rates were recorded.

RESULTS

The results of Experiment 2 are shown in Figure 3. The line graphs on the left show the

sessional response rates in each of the three phases, and the bar graphs in the middle show the phase means for the same data. The switch from tandem VI VR to tandem VR VI led to no reduction in response rate for any of the rats. The far right side of Figure 3 shows the phase means for the median reinforced IRTs. For Rats 7 and 8, which were on the tandem VI 30-s VR 10 schedule, the switch to the yoked tandem VR 10 VI x -s schedule did result in significantly longer reinforced IRTs. For Rats 5 and 6, which were on the denser tandem VI 15-s VR 5 schedule in Phase 1, however, the change to the yoked tandem VR 5 VI x -s schedule led to no change in the duration of the reinforced IRT. The phase means for interreinforcement time are not shown in Figure 3, because there was virtually no delay in reinforcement when the tandem schedules terminated in the VI component instead of the VR component, which suggests that the molar feedback functions for the two versions of the schedule were not different.

Table 2

Phase averages from Experiment 2. Standard errors of the mean appear in parentheses.

Rat	Schedule	Overall response rate (resp/min)	Median reinforced IRT (s)	Mean interfood time (s)
5	VI 15 VR 5	49.7 (10.4)	0.49 (0.07)	23.7 (4.5)
	VR 5 VI x	51.5 (5.2)	0.43 (0.17)	23.9 (4.5)
	VI 15 VR 5	52.5 (5.9)	0.46 (0.07)	21.2 (1.0)
6	VI 15 VR 5	96.4 (10.8)	0.25 (0.05)	19.5 (0.8)
	VR 5 VI x	81.0 (11.8)	0.32 (0.09)	19.5 (0.8)
	VI 15 VR 5	85.6 (10.0)	0.21 (0.05)	19.2 (0.5)
7	VI 30 VR 10	78.1 (12.3)	0.17 (0.06)	39.5 (2.2)
	VR 10 VI x	72.7 (6.9)	0.40 (0.15)	39.5 (2.2)
	VI 30 VR 10	80.0 (8.0)	0.18 (0.05)	38.3 (1.1)
8	VI 30 VR 10	69.2 (9.1)	0.21 (0.03)	40.1 (1.9)
	VR 10 VI x	76.5 (10.9)	0.43 (0.24)	40.0 (2.0)
	VI 30 VR 10	76.9 (11.4)	0.25 (0.09)	39.0 (1.7)

These data are shown in Table 2, however, along with mean interfood time.

DISCUSSION

The tandem VI 30-s VR 10 schedule and its tandem VR 10 VI x-s counterpart are the schedules that are most comparable to the schedules used in the first experiment. The data from these schedules suggest little role for the duration of the reinforced IRT in governing the rate of response on tandem VI 30-s VR 10 and yoked tandem VR 10 VI x-s schedules using rats and a lever-pressing response. The failure to observe any response-rate differences in the VI 30-s VR 10 and VR 10 VI x-s versions of the tandem schedule, the latter having longer reinforced IRTs, is not consistent with the hypothesis that differences in duration of the reinforced IRT govern response-rate differences in VR and VI schedules. The absence of any differences in the duration of the reinforced IRT when the tandem VI 15-s VR 5 schedule was changed to

tandem VR 5 VI x s is likely due to the very short IRIs associated with this schedule and the decreased likelihood for long reinforced IRTs to occur.

GENERAL DISCUSSION

On balance, these data considered together provide at least as much support for the role of response rate–reinforcement rate correlations (Baum, 1973, 1981; Rachlin, 1978; Staddon, 1979) as they do for the role of reinforced IRTs (Anger, 1956; Platt, 1979; Shimp, 1969). Also, the results taken as a whole are opposite to those reported by Peele et al. (1984), who found fairly consistent support for the influence of the reinforced IRT and little evidence for an effect of the response rate–reinforcement rate correlation on VR and VI response rates. However, the potential confounding effects associated with the multiple-schedule within-session yoking of VR and VI used by Peele et al. formed the basic reason for undertaking the present experiments. The present data are relatively free of the interpretation problems posed by schedule interaction because of the between-sessions yoking of VR and VI. Although such yoking reduces the control achieved by the yoking procedure to some extent by creating the identical patterns and rates of reinforcement in VR and VI on different days, the loss is more than offset by the elimination of the interaction problem. In addition, the within-subject between-sessions yoking utilized in the present series of experiments avoids the random-error problem associated with between-subjects within-session yoked designs that were outlined by Church (1964). On the other hand, the choice of rats and a lever-pressing response over pigeons and a key-pecking response, and the use of relatively dense reinforcement schedules, compromise the conclusion that the differences in the findings are due to the type of yoking. Peele et al. (1984) found that with pigeons and relatively lean reinforcement schedules yoked within multiple schedules, VI and VR response-rate differences were determined primarily by duration of the reinforced IRT, and they found little evidence for a role for response rate–reinforcement rate correlations. It seems clear from the present data, however, that with the use of rats, and fairly dense reinforcement schedules in which there is little possibility of schedule

interaction, VR and VI response-rate differences are not determined primarily by the duration of the reinforced IRTs but also by the response rate–reinforcement rate correlation.

As mentioned in the Introduction, there has been considerable previous research on the issue of whether behavior is primarily controlled by the reinforced IRT or by the response rate–reinforcement rate correlation, most of it employing complex or synthetic schedules and producing results that relate only indirectly to the question of what causes response-rate differences in simple VI and VR schedules.

Several investigators have used synthetic VI schedules, in which the response rate–reinforcement rate correlation is minimal, to examine the effect of the duration of the reinforced IRT on responding. Shimp (1973) varied the probability of reinforcement for successive classes of IRT in synthetic VI schedules delivering from 30 to 60 reinforcers per hour and found a systematic relationship between the rate of reinforcement of IRTs between 1 and 6 s in 0.5-s bins and the rate of emission of those classes of IRT, but found little relationship between the rate of reinforcement of IRTs between 0.1 and 0.6 s in 0.05-s bins and the rate of emission of those classes of IRT. Kuch and Platt (1976) programmed reinforcers on an interval-percentile (IP) schedule that permitted independent manipulation of reinforcement rate and the reinforcement of particular IRTs. They programmed reinforcement rates ranging from 30 to 360 per hour, with reinforcement independent of IRT duration, dependent on short IRTs, or dependent on long IRTs. They found that reinforcing long IRTs suppressed responding relative to that maintained when reinforcers were delivered without reference to IRT, but that reinforcing short IRTs had no effect on responding. Galbicka and Platt (1986) used a variation of the IP schedule that also permitted independent manipulation of reinforcement rate and reinforcement of particular IRT classes. Using average minimum IRIs of either 30 or 120 s and holding reinforcement rate constant, Galbicka and Platt varied the degree of contingency between responding and reinforcement of long IRTs for pigeons. They found increased emission of long IRTs, and concomitantly reduced response rates, as the degree of contingency increased. In the studies by Kuch and Platt (1976) and Shimp (1973), only dif-

ferential reinforcement of long IRTs, but not short IRTs, affected response rates, and in the Galbicka and Platt (1986) study, only reinforcement of long IRTs was examined and was found to affect response rate. Also, the Galbicka and Platt, Kuch and Platt, and Shimp studies all used schedules that closely resembled VI schedules and hence had molar feedback functions that specified little correlation between rate of responding and rate of reinforcement, given the rate of responding maintained by the schedules. Consequently, it is perhaps not surprising that control by long reinforced IRTs was so clearly demonstrated in those studies. Experiment 1 in the present research involved reinforcement of IRTs that were well under 1 s; this may explain their weak control over response rate. The reason for the failure of a molecular effect of IRT reinforcement in the present Experiment 2 (in which molar feedback was controlled) is not clear, but may be due to the fact that the reinforced IRTs were once again short, with the mean median reinforced IRTs being well under 1 s.

Other investigators have examined synthetic schedules in which there is a substantial response rate–reinforcement rate correlation in the absence of demonstrated reinforcement of long or short IRTs. McDowell and Wixted (1986) used human subjects to compare VR 15, 30, 60, 120, and 240 schedules to comparable VI schedules incorporating a linear feedback loop that caused the VI to resemble a VR from the point of view of a response rate–reinforcement rate correlation, while still theoretically reinforcing long IRTs. This was accomplished by redetermining the required minimum IRI after each response, based on the accumulated mean IRT since the last reinforcer. At a response rate of 60 responses per minute, these VI schedules provided average minimum IRIs of 15, 30, 60, 120, and 240 s, respectively. But any increase in response rate led to a decreased minimum-required IRI, whereas any decrease in response rate led to an increased minimum-required IRI. However, because reinforcement followed the first response after the expiration of the current IRI, the VI schedule with the linear feedback loop had the potential to reinforce long IRTs, although the authors provided no evidence that this actually happened. That notwithstanding, they found no difference in

the response rates generated by these two schedules when reinforcement rates were equated and concluded that the duration of the final IRT plays little role in the response-rate differences normally seen in VR and VI. Dawson and Dickinson (1990) compared a random-ratio (RR) 20 schedule with the same IP schedule used by Kuch and Platt (1976). An RR schedule is similar to a VR schedule in reinforcing no particular class of IRT while having a direct correlation between response rate and reinforcement rate. A yoking procedure was used, in which the animal on the RR 20 schedule determined the minimum IRIs for the animal on the IP schedule. The average IRIs determined by the RR 20 animals ranged from 10 to 20 s. Dawson and Dickinson concluded that because the RR schedule led to higher response rates than did the IP schedule, and because the schedules did not differ in duration of the reinforced IRT, the molar feedback differences between the RR and IP schedules must have been responsible for the response-rate differences observed. These studies suggest that response rate–reinforcement rate correlations exert a powerful effect on response rate in the absence of the counteracting effect of the reinforcement of long IRTs (Dawson & Dickinson, 1990) or in the possible, but unreported, presence of counteracting reinforcement by long IRTs (McDowell & Wixted, 1986). The first experiment in the present research showed a substantial effect of a response rate–reinforcement rate correlation even in the presence of a concomitant effect of reinforcement of short IRTs, although it should be noted that previous research has shown little effect of reinforcement of short IRTs on behavior (Kuch & Platt, 1976; Shimp, 1973).

Because the present research used rats, relatively dense reinforcement schedules were employed in order to ensure response rates similar to those attained by Peele et al. (1984) (who used pigeons), and the results suggest that this objective was attained. It is unlikely, however, that species and response differences are responsible for the discrepancy between the present data and those offered by Peele et al. The data of Ettinger et al. (1987), which provided strong support for IRT reinforcement, were from rats, not pigeons. Moreover, the response-rate differences usually seen in studies with pigeons that involve comparisons between VR and yoked VI were also reported

by Reed et al. (1988) who, using rats, compared VR to yoked VI as well as VI to yoked VR, with schedule parameters ranging from VR 5 to VR 30 and VI 20 s to VI 60 s. Although the VR VI response-rate differences were more pronounced with the leaner schedules, there were clear differences, with VR yielding faster response rates at all parameter values. Further research comparing various species and operant responses over a wider range of schedule parameters may help to clarify this issue.

The present data, taken together with recent empirical research, seem to suggest a role for the molar relationship between rate of responding and rate of reinforcement, as well as for the duration of the reinforced IRT, in determining response rates on simple VR and VI schedules. These data, however, do not provide insight into the microprocesses through which molar feedback principles operate at the behavioral level. Whatever that process turns out to be, it seems clear that it is not so simple a mechanism as the duration of the reinforced IRT.

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