*AN INVERSE RELATIONSHIP BETWEEN BASELINE
FIXED-INTERVAL RESPONSE RATE AND THE
EFFECTS OF A TANDEM RESPONSE
REQUIREMENT*

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Previous experiments examining the effects of adding a tandem fixed-ratio response requirement on fixed-interval schedule performance have reported inconsistent results. One variable that may account for such inconsistencies is the baseline response rate in the fixed-interval condition. This possibility was investigated in the present study. Rats were given histories with either interresponse times greater than 11 s or fixed-ratio 40 schedules of reinforcement, which engendered either relatively low or high rates of responding, respectively, in the subsequent fixed-interval condition. A tandem ratio response requirement (fixed-ratio 9) was then introduced. The effects of adding this tandem response requirement were inversely related to the baseline fixed-interval response rates; low rates of responding in the fixed-interval condition were markedly increased, whereas high rates of responding were relatively unaffected. This inverse relationship appears to be similar to the rate-dependent relations observed in behavioral pharmacology. These results may provide an explanation for the inconsistent findings reported in previous studies on tandem fixed-interval fixed-ratio schedules and suggest that principles of behavioral pharmacology research may be applicable to the study of the effects of nonpharmacological variables on schedule-controlled behavior.

Key words: tandem fixed interval fixed ratio, schedule history, rate dependency, lever press, polydipsia, rats

In the experimental analysis of reinforcement schedules, the conditions operating at the moment of reinforcement are important determinants of response rate (Ferster & Skinner, 1957; Morse, 1966). Empirical and formal analyses have shown that fixed-interval (FI) schedules preferentially reinforce long interresponse times (IRTs); this may contribute to the overall rates of responding observed on that schedule (Dews, 1969; Ferster & Skinner, 1957; Morse, 1966). With FI schedules, the contribution of the preferential reinforcement of long IRTs to overall response rate can be determined by changing the requirements at reinforcement. One way to modify the conditions operating at the moment of reinforcement under FI schedules is to impose a tandem fixed-ratio (FR) response requirement (tandem FI-FR); FR schedules preferentially reinforce

short IRTs (Morse, 1966). If response rates increase with the tandem response requirement, it suggests that the conditions operating at the moment of reinforcement contribute to the response rates obtained with that schedule.

Surprisingly, when tandem FR response requirements have been added to FI schedules, inconsistent results have been obtained across studies. One study reported that the addition of an FR requirement resulted in large increases in overall response rates (Ferster & Skinner, 1957, pp. 415-422). Other studies, in contrast, have reported only modest increases (Zeiler & Buchman, 1979), slight decreases, or no change in response rates (Dews, 1969). A procedurally different but relevant study was conducted by Killeen (1969), who yoked four pigeons to four lead birds responding under FR 25, 50, 75, and 100 schedules. Food was delivered to the yoked birds for the first response emitted after the lead bird completed the FR. Although the yoked birds were formally on a variable-interval (VI) schedule of reinforcement, the schedule was actually a reasonable equivalent of an FI schedule because the leaders' behavior was stable (Zeiler

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& Buchman, 1979). Killeen then added a tandem response requirement to the yoked pigeons' schedule. The effect of the tandem response requirement was to either increase response rates or to leave overall response rates relatively unchanged.

The variables responsible for these inconsistent results have yet to be determined. All of the above studies employed FR 9 to 12 response requirements but used different FI parameters, suggesting that the inconsistencies may result from the particular FI parameter selected or the resulting reinforcement rates (Zeiler & Buchman, 1979). However, another variable that may account for the discrepancies is the baseline FI response rate prior to the addition of the FR requirement (Sidman, 1960, pp. 146–148). For example, pigeons in Ferster and Skinner's (1957) study exhibited very low response rates under the FI schedule, whereas those in the studies of Dews (1969) and Zeiler and Buchman (1979) exhibited relatively higher response rates. Killeen's (1969) pigeons exhibited a variety of response rates. This suggests that an inverse relationship may have existed between the baseline response rate and the proportion of change such that the addition of the FR produced large increases in low-rate FI performance (Ferster & Skinner, 1957; Killeen, 1969), whereas higher rate FI performance was unchanged, increased, or decreased slightly (Dews, 1969; Killeen, 1969; Zeiler & Buchman, 1979). This inverse relationship may be similar to the phenomenon referred to as rate dependency, which has been extensively researched in behavioral pharmacology (Dews, 1958; Dews & Wenger, 1977; Sanger & Blackman, 1976).

To investigate whether the effects of adding a tandem FR requirement to an FI schedule is a function of the baseline response rate, both low and high rates of responding need to be engendered under the same FI parameter. To accomplish this in the present experiment, we provided subjects with either FR or IRT $> t$ -s schedule histories, which have been demonstrated to result in relatively high- and low-rate FI performances, respectively (Weiner, 1964). Effects of these same schedule histories have been previously studied with regard to between-subject differences in human FI performance (Weiner, 1964, 1969) and the rate-dependent effects of amphetamine (Urbain, Poling, Millam, & Thompson, 1978). More

recently, these histories have been used to study the potential mechanisms by which history influences current behavior (Johnson, Bickel, Higgins, & Morris, *in press*). In the present study, we varied schedule history to investigate the influence of baseline response rate on the effects of adding a tandem FR requirement.

METHOD

Subjects

Six adult male Sprague-Dawley rats (Charles River) were maintained at 80 to 85% of their free-feeding weights. They were housed individually with free access to water in a temperature-controlled room.

Apparatus

An experimental chamber (26 by 26 by 18 cm) was equipped with a response lever, pellet dispenser, food tray, and metal drinking spout. The food tray was centered on the front wall of the chamber, 2 cm above the grid floor, and protruded 3 cm into the experimental space. The lever was located to the left of the food tray, 3 cm above the grid floor. Each depression of the response lever exceeding 0.20 N operated a 28-V DC relay producing an audible click. The water spout was attached to a 100-mL calibrated reservoir and projected 0.5 cm into the chamber through a circular hole 4 cm to the right of the food tray.

The chamber was contained inside a Grasson-Stadler chest (Model E3125AA-300). A red stimulus light mounted above the food tray was illuminated continuously during experimental sessions, and an exhaust fan positioned on the side of the chamber provided ventilation. A white-noise generator was in operation during experimental sessions. The chamber was located in a room adjacent to the area containing the electromechanical scheduling and recording equipment. Responses were recorded via electrical impulse counters. Water intake was determined by measuring the volume (mL) of water in a calibrated drinking tube before and after the session and recording the difference.

Procedure

All subjects were trained initially to lever press under an FR 1 schedule. When they responded consistently without appreciable pausing, the FR requirement was increased

gradually to 40 for Subjects S81 and S82, and the remaining 4 subjects (S21–24) were exposed to an IRT > 11-s schedule. The FR and IRT > *t* sessions constituted the schedule histories, the parameters for which were selected to produce an approximately equal rate of reinforcement across schedules and to replicate the findings of Urbain et al. (1978).

Sessions began 5 min after the subjects were placed in the experimental chamber and were terminated upon the presentation of 30 Bio-serve food pellets (45 mg). Sessions were conducted 6 or 7 days per week at approximately the same time each day. All subjects had free access to a full water bottle during the IRT > 11-s and FR history sessions. Response rate was considered stable when no increasing or decreasing trends were apparent across nine sessions. When the stability criterion was met under the FR and IRT > 11-s schedules, the schedule was changed to an FI 15-s schedule. For this and each subsequent change in schedule conditions, the change was instituted after the delivery of the 15th pellet delivery within a session. Once stability was obtained under the FI 15-s schedule, a tandem FR requirement was added such that the completion of the 10th response after the FI had timed out would result in pellet delivery (tandem FI 15 s FR 9). After stable performance was obtained on the tandem FI-FR schedule, a within-subject replication was conducted. During the replication, subjects were returned to the FI 15-s schedule until responding was stable and were again exposed to the tandem FI-FR schedule. The number of sessions in each condition is displayed in Table 1.

RESULTS

The response rates for the last nine sessions of each condition for each rat are presented in Figure 1. The top two panels show the results of rats with FR histories. During the FR 40 schedule condition, R81's and R82's mean response rates were 155.3 and 129 responses per minute, respectively. Under the FI schedule, R81's and R82's mean response rates were 143.34 and 112.12 responses per minute, respectively. The addition of the tandem FR requirement produced relatively small effects in these 2 subjects. Response rates decreased 4.1% to a mean of 137.48 responses per minute for R81, whereas R82's response rate increased

Table 1
Number of sessions per condition.

Subject	FR		FI	TAND	FI	TAND
	1–39	FR 40				
R81	69	11	29	15	22	19
R82	70	23	50	9	29	43
IRT > 11 s						
R21		62	21	30	76	26
R22		77	34	15	17	27
R23		113	38	26	13	27
R24		109	43	53	20	19

9% to a mean of 122.12 responses per minute. Upon return to the FI schedule, R81's mean response rate was 103.5 responses per minute; R82's response rate was 112.99 responses per minute. The second exposure to the tandem schedule in these 2 subjects produced a similar small effect with R81's response rate decreasing 6.5% to a mean of 97.79 responses per minute and R82's response rate increasing 12.7% to mean of 127.38 responses per minute. Across all conditions, the pattern of responding exhibited by these subjects was characterized by relatively constant responding with little pausing.

The lower four panels of Figure 1 show the results from each condition for rats with IRT > 11-s histories. These rats exhibited relatively low response rates on the IRT > 11-s schedule ranging from 4.61 to 7.58 responses per minute. Under the FI 15-s schedule, mean response rates for R21, R22, R23, and R24 were 28.82, 9.05, 6.18, and 15.3 responses per minute, respectively. For R22, R23, and R24, imposition of the tandem response requirement resulted in relatively large increases in response rate (1.4- to 3.5-fold increases); mean response rates were 21.49, 21.8, and 22.06 responses per minute, respectively. This general effect was replicated with all of these rats, although the magnitude of the increases was greater during the replication than during the first exposure (5.2- to 6.5-fold increases). The typical pattern of behavior during the FI schedule was characterized by long pauses followed by one or a small number of responses. During the tandem condition, response patterns were characterized by long pauses followed by a burst of responding.

The results for R21, the fourth rat with an IRT > 11-s history, were different from the

Fig. 1. Response rates are shown for rats with FR histories (top two panels) and IRT > *t*-s histories (bottom four panels) during the last nine sessions of each condition. The sequence of conditions was history condition (FR 40 or IRT > 11 s), FI 15 s, tandem FI 15 s FR 9, FI 15 s, and tandem FI 15 s FR 9. Note the change in scale between rats with FR and IRT > *t*-s histories.

Table 2

Mean and standard deviation of responses per minute, reinforcers per minute, and mL of water consumed during the last nine sessions of each condition.

Subject	FR	FI	TAND	FI	TAND
R81					
Responses per minute	155.3 (10.97)	143.3 (6.73)	137.4 (9.8)	103.5 (8.39)	97.8 (6.52)
Reinforcers per minute	3.7 (0.25)	4.0 (0.31)	3.3 (0.17)	4.0 (0.07)	3.2 (0.15)
mL	0.11 (0.33)	0.0 (0.0)	0.0 (0.0)	0.11 (0.33)	0.0 (0.0)
R82					
Responses per minute	129.0 (8.0)	112.1 (6.35)	122.5 (6.64)	113.0 (7.39)	127.4 (9.53)
Reinforcers per minute	3.18 (0.20)	3.99 (0.09)	3.16 (0.07)	3.93 (0.09)	3.26 (0.06)
mL	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.89 (0.78)	0.56 (0.73)
IRT > 11 s					
R21					
Responses per minute	7.58 (0.58)	28.82 (3.82)	28.08 (2.58)	4.54 (0.88)	24.08 (1.52)
Reinforcers per minute	2.65 (0.30)	4.00 (0.27)	2.17 (0.16)	3.34 (0.25)	2.28 (0.14)
mL	1.11 (1.76)	0.22 (0.67)	11.0 (2.0)	13.67 (1.58)	16.33 (1.73)
R22					
Responses per minute	4.78 (0.47)	9.05 (2.23)	21.49 (4.26)	4.68 (0.65)	26.53 (2.05)
Reinforcers per minute	3.89 (0.21)	3.75 (0.19)	1.91 (0.31)	3.35 (0.19)	2.32 (0.18)
mL	13.89 (1.76)	14.22 (1.09)	17.78 (1.48)	14.79 (1.20)	17.78 (1.48)
R23					
Responses per minute	4.61 (1.13)	6.18 (1.17)	21.8 (3.02)	3.34 (0.48)	21.85 (0.84)
Reinforcers per minute	3.72 (0.21)	3.56 (0.22)	1.97 (0.21)	2.87 (0.27)	2.06 (0.15)
mL	12.11 (1.76)	12.0 (1.23)	19.22 (3.11)	15.56 (2.3)	18.59 (1.59)
R24					
Responses per minute	4.87 (0.94)	15.3 (3.15)	22.06 (1.35)	4.12 (0.69)	21.3 (1.22)
Reinforcers per minute	3.69 (0.32)	4.00 (0.10)	2.12 (0.13)	3.45 (0.26)	2.03 (0.11)
mL	13.89 (1.45)	12.44 (1.51)	20.56 (3.4)	15.78 (1.2)	20.0 (1.58)

other rats with this history. During his first exposure to the tandem condition, response rates decreased 2.6%. However, the second exposure to the tandem condition resulted in a large (5.3-fold) increase, similar to the effect seen in the other rats with IRT > 11-s histories.

Table 2 shows the overall mean and standard deviations for the final nine sessions of each condition for response rate, reinforcement rate, and water consumption. Effects on response rate have been described above. The tandem schedule decreased reinforcement rate relative to the FI schedule for all rats inde-

Fig. 2. The relationship between the effects of adding a tandem response requirement and baseline FI response rates. Effects are expressed as a proportion of baseline FI response rates. Data from other studies were taken from tables or estimated from figures contained in those reports.

pendent of reinforcement history. Water consumption increased during the tandem schedule condition relative to the FI condition for rats with $IRT > 11$ -s histories but not for those with FR histories.

Rate Dependency

To ascertain whether the effects of the tandem response requirement were inversely related to the response rates in the FI condition, the data from the present study are presented in a rate-dependency plot (Figure 2). Also included in this plot are data from the other studies of tandem FI-FR (Dews, 1969; Ferster & Skinner, 1957; Killeen, 1969; Zeiler & Buchman, 1979). This plot displays the proportion of change in response rate from baseline FI to tandem FI-FR plotted as a function of the baseline FI response rate. The curve fitted to these data is a logarithmic regression of the data across all of the studies. As FI response rate increased, the proportional increase in response rate in the tandem condition progressively decreased both within the current study and across the other studies.

DISCUSSION

The purpose of the present study was to determine whether the effects of adding a tandem response requirement to an FI schedule

depended on the baseline FI response rate. To vary response rates at a single FI parameter, different schedule histories were provided to the subjects. $IRT > t$ -s and FR schedule histories resulted in relatively low and high rates of FI responding, respectively. The imposition of a tandem response requirement upon these low- and high-rate FI performances showed that relative magnitudes of changes in response rates obtained under the tandem schedule were inversely related to the baseline FI response rate; low-rate FI performance was markedly increased by the tandem response requirement, but high-rate FI performance was relatively less affected.

Response rates in the tandem condition, however, were not necessarily history dependent. Subject R21 from the $IRT > t$ -s history condition, for example, initially exhibited higher rates of responding in the FI condition than did other subjects with this history, and the first exposure to the tandem response requirement produced a minimal effect on response rate. During the replication, R21 exhibited lower rates in the FI condition and the tandem condition produced a large increase in response rate. This suggests that the arranged history was not the sole determinant of the inverse relationship and that this effect may depend more on the response rates themselves or on other factors that determined those rates.

FI parameter and reinforcement rate differed within and across the earlier studies of tandem FI-FR schedules. Zeiler and Buchman (1979) suggested that these differences may be responsible for the discrepancies observed. In the present study, reinforcement rate was held relatively constant, while response rates were varied via behavioral histories. Under these conditions, we observed an inverse relationship between FI response rate and the effects of the tandem FR requirement. A similar inverse relationship was found when data from the earlier studies were displayed in a rate-dependency plot (see Figure 2). Given the similarity between our findings and the earlier findings, we suspect that differences in reinforcement rate do not account for the discrepant results previously observed. Of course, further studies manipulating response and reinforcement rates independently will be necessary to determine the relative contribution of these two variables.

The inverse relationship between FI response rate and the effects of an added tandem FR requirement may be similar to that observed often in behavioral pharmacology (i.e., rate dependency). Rate dependency refers to the observation that the effects of a drug on response rate are inversely related to the pre-drug rates of responding. Previous studies have shown that noise and drugs produce similar rate-dependent effects within subjects (Howell, Byrd, & Marr, 1986; McKim, 1981). A similar within-subject examination will be necessary to compare directly whether the tandem response requirement and drugs produce similar rate-dependent effects. Nonetheless, the present findings suggest that the principle of rate dependency may be an important consideration in the analysis of the effects of non-pharmacological variables on schedule-controlled behavior (cf. Sidman, 1960).

Although we were able to vary response rate while holding reinforcement rate constant, it is important to note that we did not separate the contributions of response rate and water consumption. If the results obtained in the present study were due primarily to the factors that engendered low- and high-rate responding (e.g., water consumption), and not to the response rates per se, then the results of the present experiment may have limited generality. In the present study, water consumption seemed to have a prominent role in determining response rate and may have been the pri-

mary determinant of the results obtained. In an earlier study, we observed that rates of lever pressing under FI schedules were dependent on the opportunity to engage in polydipsia (Johnson et al., in press). In that study, subjects with IRT > 11-s histories exhibited low rates of responding when the opportunity to engage in drinking was available. However, when engaging in drinking was constrained by limiting the amount of water available or by the removal of all water, substantially higher rates of lever pressing occurred. In the present study, data from Subject R21 are consistent with this finding. This subject did not drink during his first exposure to the FI and exhibited response rates higher than the other rats with IRT > 11-s histories. At that time the addition of the tandem response requirement produced only a minimal effect. R21 did drink during the subsequent FI condition, and when the tandem was reintroduced response rates increased considerably. This experiment with R21 confirms our previous finding that polydipsia is one means by which history may exert its effects on ongoing operant behavior. It remains unclear whether the results obtained in the present study are limited to arrangements in which drinking or some other adjunctive response is available. Future research should ascertain whether low and high response rates induced via other methods, such as pacing contingencies (MacPhail & Gollub, 1975), will yield similar results.

Morse (1966), in discussing the contribution of Ferster and Skinner (1957) to the study of schedule-controlled behavior, stated that they emphasized "the importance of the prevailing conditions at the moment of reinforcement, the importance of the subjects' own behavior to the development of stable performance, and especially that rates of responding interact with schedules to control subsequent rates of responding" (p. 67). In the present study, each of these variables appeared to interact to contribute to our results: (a) We showed that changing the conditions operating at the moment of reinforcement via a tandem response requirement can markedly influence FI performance when low rates of responding are initially exhibited on that FI schedule. (b) We also found evidence that subjects' other behavior can contribute to the rates of responding obtained on FI schedules. Although not consuming water, R21's rates of responding under

the FI schedules were relatively higher than other rats with $IRT > t$ -s histories. However, when R21 began drinking, FI response rate was comparable to those of the other rats with $IRT > t$ -s histories. (c) Finally, we found that rates of responding on FI schedules interacted with the tandem response requirement such that low-rate FI performance was markedly increased while higher rate FI performance was relatively unaffected. Thus, results of the present study suggest that the variables outlined by Morse (1966) are important determinants of schedule-controlled behavior. These variables are always operating even when they are not studied explicitly, as may have been the case with several of the previous studies of tandem FI-FR. Although the degree of control exerted by these variables may vary as a function of the schedule arrangement under study, their importance should not be underestimated in the study of schedule-controlled behavior.

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