RESPONSE REQUIREMENTS AS CONSTRAINTS ON OUTPUT

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Two experiments studied how added response requirements affected fixed-interval schedule performance. Experiment 1 involved tandem fixed-interval fixed-ratio schedules, and Experiment 2 studied conjunctive fixed-interval fixed-ratio schedules. In both, pigeons' output, defined as overall response rate or as responses during the interval, first increased and then decreased as the ratio was raised. With small ratio requirements, the frequency of reinforcement in time either did not change or decreased slightly. With progressively larger ratios, reinforcement frequency decreased consistently. Alternative explanations were discussed. The first, a reinforcement theory account, was that response strength is an increasing monotonic function of both the response requirement and reinforcement frequency, and the bitonic output function represents interacting effects. Increases in the response requirement accompanied by small changes in reinforcement frequency enhance output, but further increases result in large enough decrements in reinforcement frequency so that output is lowered. The second explanation does not view reinforcement as a basic process but, instead, derives from concepts of economics and conservation. Organisms allocate their behavior among alternatives so as to maximize value, where value is a function of the responses that can occur in a given situation under the set of restrictions imposed by particular schedules. One form of this theory explicitly predicts that output is a bitonic function of ratio requirements in simple ratio schedules. However, it was not clear that this model could explain the present effects involving joint ratio and interval schedule restrictions.

Key words: output, tandem FI FR schedules, conjunctive FI FR schedules, response number requirements, reinforcement frequency, reinforcement theory, economic theory, key peck, pigeons

Comparisons among reinforcement schedules reveal that response output is not the simple outcome of reinforcement input. Instead, output varies with the degree of constraint imposed by various schedules, where constraint refers to the degree of invariance in output (number of responses) imposed by the particular scheduling arrangement. The importance of constraint is highlighted in conservation theory (Allison, 1976), which views reinforcement schedules in terms of the way they restrict the allocation of responses among various alternatives.

Maximal constraint occurs in situations involving rigid numerical requirements; minimal constraint occurs when the number of responses is totally free to vary. The extreme cases are manifested by ratio and time schedules. Ratio schedules rigidly proscribe response number, so output per consequence is not free to vary at all. In contrast, time schedules demand no responses, so output has neither upper nor lower limits. The outcomes of these extremes are well known. Total constraint maintains the target response at a high rate until the output requirement becomes excessive, and then responding stops (cf. Ferster & Skinner, 1957). Total absence of constraint often results in superstitious responding characterized by frequent changes in the predominating behavior, and any specific response may or may not occur (cf. Zeiler, 1972).

The data from the extreme cases would suggest that output might approximate a monotonic function of degree of constraint (or is the product of a feedback function where obtained rate of reinforcement is response rate divided by the response requirement), but this generality is contradicted by performance with

other schedules. Interval schedules require only a single response per reinforcer, and therefore differ but slightly from time schedules on the constraint continuum (and in the limit imposed on the frequency of reinforcement in time). Yet fixed-interval schedules easily generate as many responses as do fixed ratios, and in fact, readily produce far more responses than can be maintained by large fixed ratios (Ferster & Skinner, 1957; Zeiler, 1977, 1979). At high parameter values, then, the single response requirement of interval schedules generates more output than do arrangements demanding either more responses or no responses at all. Apparently, the combined effects of a single response requirement and a fixed minimum interreinforcer interval are quite different from the individual effects of either. This then raises the question of how output would be affected when multiple response requirements are added to a fixed-interval schedule.

The present experiments constrained output in fixed-interval-based schedules by requiring more than the single response to produce the reinforcer. The specific arrangements were tandem and conjunctive fixed-interval (FI) fixed-ratio (FR) schedules. Both the tandem and the conjunctive schedules added fixed-ratio requirements to fixed-interval schedules without providing any stimulus event to signal when the various components had or had not been completed. Parametric manipulations of the FR value provided information about the relation between added constraint and output, and they also clarified some apparently discrepant and contradictory data already in the literature.

EXPERIMENT 1:
TANDEM FI FR SCHEDULES

The tandem FI FR schedule replaces the single response requirement of the simple FI with the sum of that response and those required by the FR: Minimum output is the FR value plus one. No matter how many or few responses are emitted during the FI, reinforcer delivery cannot occur until the FR is completed, and the FR is not in effect until the first response following the specified time period has terminated the FI. The tandem schedule differs from the simple FI in requiring

these additional responses after the end of the interval, and it differs from the simple FR in imposing the FI time period as the minimum time that must elapse between successive reinforcements. Because reinforcement frequency is constrained by the FI component, the tandem schedule does not permit a positive feedback loop between response rate and the frequency of reinforcement in time. Reinforcement frequency must be lower with the tandem than with the FI alone, because the time taken to execute the ratio must be added to the interval value.

Existing data on tandem FI FR schedules are confusing. On the one hand, Ferster and Skinner (1957) compared a tandem FI 45-min FR 10 with a simple FI 45-min schedule. Given the large number of responses emitted by pigeons with FI schedules of this magnitude, both the added 10 response requirement and the necessary added time would seem inconsequential. Yet response rates were substantially higher with the tandem schedule. On the other hand, Dews (1969) found no difference in pigeons' response rates with FI 3-min, tandem FI 3-min FR 1, and tandem FI 3-min FR 9 schedules. Killeen (1969) yoked four pigeons to four lead birds given FR schedules of 25, 50, 75, and 100. The yoked bird received food for the first response emitted after the partner completed the FR. Strictly speaking, the yoked birds were on variable-interval schedules, but the leaders' stable response rates produced a reasonable equivalent to FI. Then a tandem FR requirement was added to the derived interval schedule. Compared with the simple yoked interval, overall response rates with the tandem schedule sometimes increased slightly, sometimes decreased slightly, or did not change as the FR value was increased from 3 to 6 to 12.

Perhaps these differences in results stemmed from the FI parameter value: The study finding substantial rate increases with the tandem used a much longer interval than did the others. Or perhaps interval and ratio size interact such that the various experimenters happened to select fortuitous combinations that gave them their particular results. The obvious need was for a parametric analysis. In the present experiment, interval size was manipulated from 3 to 30-min between subjects, and ratio size was varied systematically from 5 to 640 for each subject.

METHOD

Subjects

Three White Carneaux pigeons were maintained at 80% of their free-feeding weights. All had prior experience with a variety of reinforcement schedules, but none had ever been exposed to tandem schedules.

Apparatus

The experimental chamber was a single-key pigeon unit. The 2-cm diameter response key was operated by a minimum force of .18 N and could be transilluminated by two 1.1-W red lamps. A 5-cm square aperture centered 10 cm below the key and 10 cm above the floor provided occasional access to Purina Pigeon Checkers, a birds' standard diet. During the 3-sec feeder cycles, a 1.1-W white lamp illuminated the aperture, and the keylight was off. White noise and a continuously operating exhaust fan masked extraneous sounds.

Procedure

Table 1 shows the sequence of conditions and number of sessions for each bird. Sessions began with a food delivery followed by onset of the red keylight. During the baseline FI schedules, the first response occurring after the interval elapsed was followed by food delivery, and then the next interval began. In the tandem FI FR schedules, the first response emitted after the interval elapsed produced no exteroceptive stimulus event but simply insti-

tuted the FR component. Completion of the ratio resulted in food delivery and then the next cycle.

The FI values were 3, 10, and 30 min for Birds 16, 135, and 105 respectively. The FR values increased geometrically by a factor of 2.0, beginning with FR 5 and ending with FR 640. After the ascending series of ratios, tandem ratios of 160, 40, and 10 were imposed in that order. Then the original FI schedules occurred again.

Because each increment in FR size increased the time period between food presentations, it seemed useful to determine whether effects of the schedules could be due to reinforcement frequency itself. To evaluate this possibility, the last five sessions of one tandem FI FR schedule (FR 640, 320, and 160 for Birds 16, 135, and 105 respectively) were used to generate five variable-interval (VI) schedules, each of which matched the sequence of interfood intervals occurring in the corresponding tandem schedule session. This yoking procedure meant that the VI and the last five sessions of the tandem schedules were virtually identical in interfood time, the difference being that the VI required only one response but the tandem schedule required the ratio plus one. This yoked control was the final condition. Each of the five VI schedules was used in repeating order.

A condition was maintained until performance met a stability criterion. Beginning with the fourth session of each condition, overall

Table 1

Sequence of Conditions: Experiment 1

		Number of sessions		
Condition	Schedule	Bird 16 FI 3-min	Bird 135 FI 10-min	Bird 105 FI 30-min
1	Simple FI	44	65	63
2	Tandem FI FR 5	21	27	26
3	Tandem FI FR 10	18	39	20
4	Tandem FI FR 20	35	39	33
5	Tandem FI FR 40	39	39	39
6	Tandem FI FR 80	16	18	18
7	Tandem FI FR 160	19	19	20
8	Tandem FI FR 320	35	35	36
9	Tandem FI FR 640	43	42	41
10	Tandem FI FR 160	15	19	17
11	Tandem FI FR 40	18	19	16
12	Tandem FI FR 10	18	19	18
13	Simple FI	15	16	16
14	VI Yoked Control (yoked to FR)	22 (FR 640)	25 (FR 320)	25 (FR 160)

response rate in the session was computed for each bird. Performance was considered stable when three consecutive medians of blocks of three session rates (involving nine consecutive sessions) showed no consistent increase or decrease. This criterion ensured a minimum of 12 sessions. Typically, conservatism and convenience resulted in conditions continuing beyond criterion, but the last nine sessions always did meet the criterion even when it had been met earlier.

Sessions were conducted 7 days per week and continued for 21 food presentations. If this did not occur within 5 hr for Birds 16 and 135 or within 10 hr for Bird 105, the session terminated with the first food delivery after these deadlines elapsed.

RESULTS

Figure 1 shows response rates averaged over the final nine sessions of each condition. With the change from FI to tandem FI FR 5, re-

sponse rate increased. With still larger ratios, rate increased further and then decreased. The form of the curve relating ratio size to response rate was independent of the FI parameter value, the only apparent difference being the particular ratio at which the rate peaked. Replications of schedules are not shown because they yielded virtually identical results. Table 2 shows that the variability in rate depended on neither the FI nor the FR values, but resembled that previously observed for simple FI schedules (Zeiler & Davis, 1978). The yoked VI control conditions (extra data points in Figure 1) produced higher rates than did the tandem schedules from which they were derived. This indicated that the rate decrease at the higher ratios stemmed not from reinforcement frequency but rather from the ratio requirements themselves.

Figure 2 shows the average number of responses during the FI components for the same sessions. The shapes of these curves closely re-
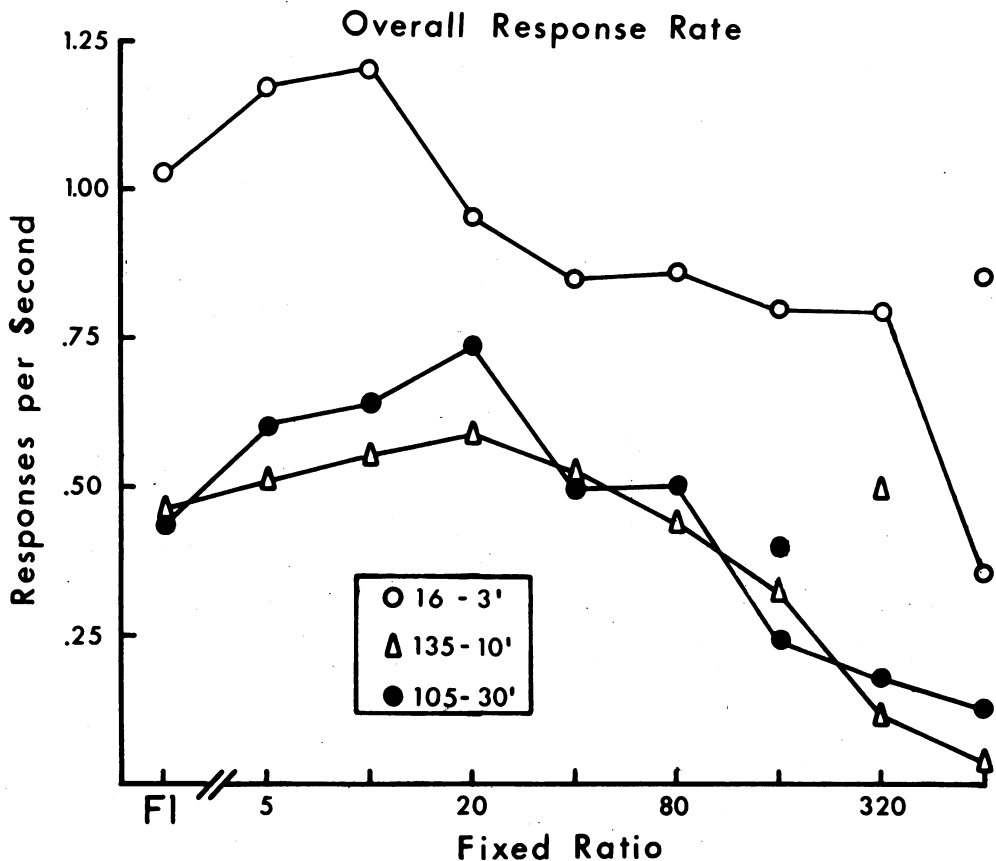

Fig. 1. Overall response rate with the tandem FI FR schedules. The extra data points are for the yoked interfood interval control conditions. The parameter value of the FI schedule appears next to each bird number.
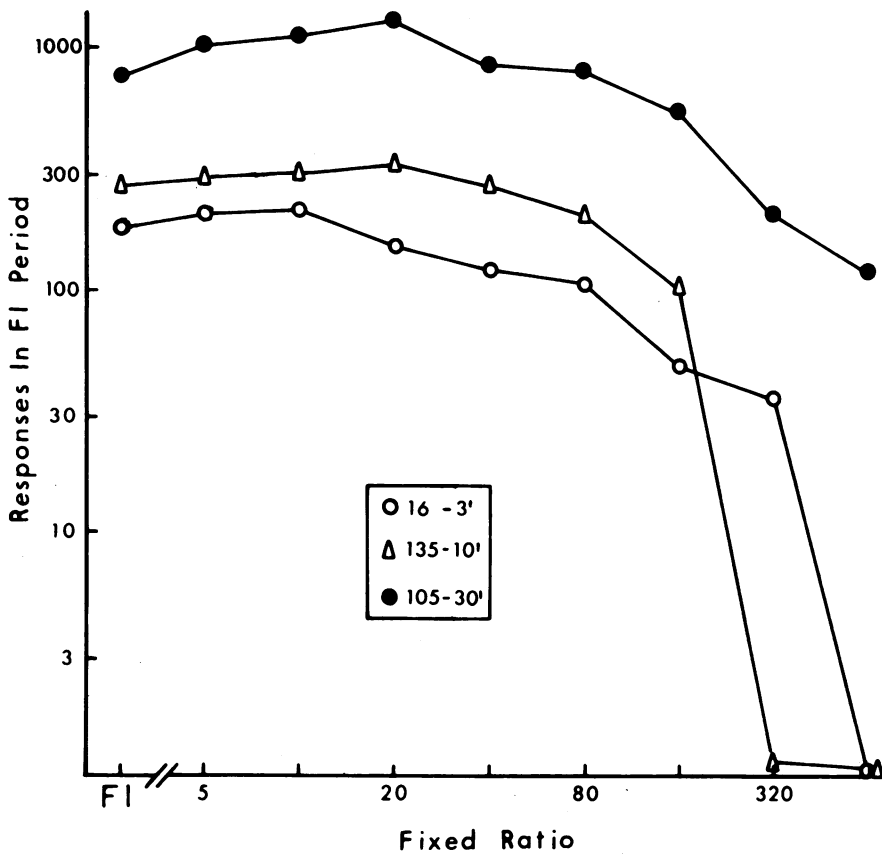
Fig. 2. Average number of responses in the FI period of the tandem FI FR schedules.

sembled those of Figure 1. With the response numbers transformed into response rates during the FI, as FR size was increased beyond that producing the peak in the curves, FI rate did decrease more rapidly than did overall rate. Two of the birds essentially stopped responding during the interval period with the highest FR schedules. Table 2 indicates that session-to-session variability did not change systematically until the ratio values resulted in greatly weakened tendency to respond during the FI period.

Measures of responding involving other segments of the total performance also showed a bitonic relation to the ratio requirement. Figure 3 shows that the average rate of responding from the first to the final response (the running rate) also rose and fell as the ratio increased. For Bird 105, the running rate peaked at a higher FR value than did overall rate, but for the other two birds the

highest running and overall rates appeared with the same ratio.

Figure 4 shows the average response rate during the FR component alone, that is, the rate of responding after the interval requirement had been completed. The FR rates showed the same general curves as did overall rate, FI responses, and running rate, although they were less regular over the entire range of ratios. The largest irregularity occurred with Bird 16, where FR 320 produced substantially higher rates than did either FR 160 or FR 640.

The cumulative records of Figure 5 are from selected conditions for one bird; however, they are reasonably representative of other birds and conditions as well. With the simple FI schedule, output varied from one interval to the next, and this variability persisted with the tandem schedules, at least until total responses closely approximated the ratio requirement. Pause duration tended to

Table 2

Means and Standard Deviations: Experiment 1

	FI	Tandem FI FRn							
		$n = 5$	$n = 10$	$n = 20$	$n = 40$	$n = 80$	$n = 160$	$n = 320$	$n = 640$
Bird 16									
Overall rate (resp/sec)	1.1	1.2	1.2	1.0	.8	.9	.8	.8	.3
	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)
Responses per interval	192	207	212	160	126	112	50	38	.1
	(22)	(23)	(36)	(22)	(22)	(16)	(14)	(25)	(.1)
Running rate (resp/sec)	1.5	1.7	(2.0)	1.6	1.6	1.8	1.7	1.2	.5
					(Standard deviations not available)				
FR rate (resp/sec)		1.6	(2.0)	2.1	2.1	2.2	.8	1.6	.6
		(.3)	(.4)	(.3)	(0.2)	(.2)	(.1)	(.3)	(.2)
Interfood interval (sec)	183	185	186	190	200	218	270	451	1883
	(.3)	(1)	(1)	(2)	(2)	(5)	(33)	(37)	(147)
Pause (sec)	53	62	71	79	97	108	144	159	613
	(10)	(9)	(7)	(7)	(8)	(9)	(20)	(21)	(219)
Bird 135									
Overall rate (resp/sec)	.5	.5	.5	.6	.5	.4	.3	.1	.1
	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)
Responses per interval	270	294	300	330	276	210	102	1	.4
	(72)	(60)	(84)	(36)	(24)	(48)	(66)	(2)	(.1)
Running rate (resp/sec)	.7	.9	.8	1.2	1.1	1.0	.8	.4	.1
					(Standard deviations not available)				
FR rate (resp/sec)		1.1	1.2	1.3	1.0	1.2	1.0	.5	.1
		(.4)	(.1)	(.1)	(.3)	(.1)	(.1)	(.3)	(1·)
Interfood interval (sec)	599	599	596	605	627	670	830	3020	13881
	(4)	(11)	(3)	(15)	(8)	(33)	(32)	(530)	(3885)
Pause (sec)	220	248	219	302	327	370	499	2105	7675
	(21)	(23)	(36)	(22)	(7)	(3)	(84)	(410)	(2892)
Bird 105									
Overall rate (resp/sec)	.4	.6	.6	.7	.5	.5	.2	.1	.1
	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)
Responses per interval	774	1062	1134	1314	882	846	576	216	126
	(90)	(144)	(144)	(198)	(162)	(127)	(198)	(54)	(145)
Running rate (resp/sec)	.6	.8	.9	1.1	1.0	1.3	.4	.3	.2
					(Standard deviations not available)				
FR rate (resp/sec)		1.5	1.7	1.8	1.4	1.7	.8	.9	.9
		(.3)	(.3)	(.6)	(.4)	(.3)	(.8)	(.7)	(.8)
Interfood interval (sec)	1764	1790	1818	1813	1834	1889	3014	4267	9614
	(3)	(20)	(20)	(14)	(28)	(42)	(492)	(544)	(1258)
Pause (sec)	378	366	563	623	(901)	1185	1362	2475	5623
	(59)	(109)	(104)	(61)	(132)	(93)	(329)	(586)	(1628)

increase along with ratio size, but it too was variable from one interfood period to the next. Responding typically was maintained once it began, with the prevailing pattern varying between gradually accelerating rate to an abrupt shift from pausing to responding at a sustained rate. With the largest FR values, the initial pause often extended well beyond the interval parameter value.

Figure 6 shows both the average interfood interval and the average initial pause duration for each schedule. As can be seen from the generally parallel solid and dashed lines connecting each set of data points, interfood interval and pause duration tended to vary together, although occasional departures from perfect covariation did occur. Both increased as a fairly monotonic function of ratio size, with the largest changes appearing with the intermediate and largest ratios.

The interresponse time (IRT) preceding food delivery was recorded during the last
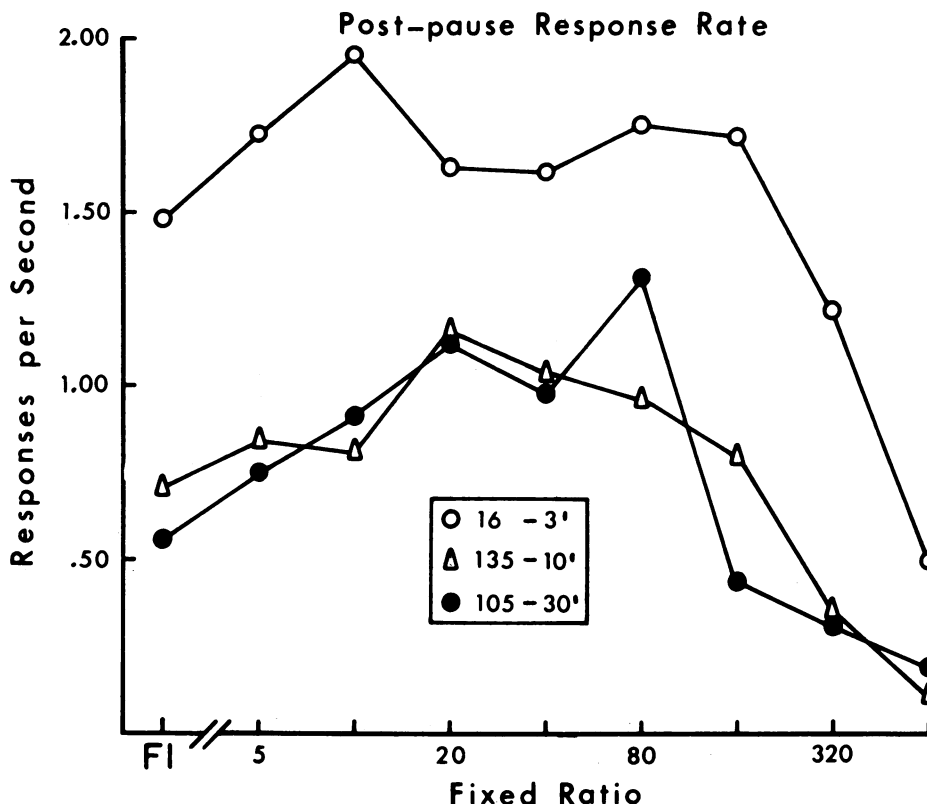
Post-pause Response Rate

Fig. 3. Response rate from the first to the last response (running rate) with the tandem FI FR schedules.

four sessions of every condition except the yoked VI control. As seen in Figure 7, the median terminal IRT was shorter with all of the tandem schedules than with the simple FI, but it did not differ among the tandem schedules themselves. The modal IRTs (.5 sec for Bird 135 and .2 sec for Birds 16 and 105) were constant in all conditions. The mean terminal IRTs revealed a function similar to the median; however, it was less regular due to occasional very long IRTs. These long IRTs resulted in an approximately linear decreasing function relating mean IRT to ratio value; however, this was less representative of the actual behavior than was the median because the frequency of IRTs between the median and the longest values did not change. The terminal IRTs, excluding the aberrant very long ones, tended to be less variable as FR size increased.

DISCUSSION

Whether defined as number of responses or as number of responses per unit time (response

rate), output first increased and then decreased when tandem response requirements were added to FI schedules. This description characterized overall output and output in the FI and FR components separately, and it did not depend on the parameter value of the FI schedule. The various results of previous experiments probably stemmed from fortuitous selection of particular ratio values: Choice of any one or two values could lead to the conclusion that tandem FI FR schedules either increase, decrease, or do not change output compared to simple FI schedules. Only the parametric analysis reveals that output is a bitonic function of ratio size in tandem FI FR schedules.

Output in tandem FI FR schedules cannot be explained by reference to selective IRT reinforcement. With all tandem ratios, the terminal IRT was shorter than it was with the simple FI schedule, as can be deduced from a formal analysis of interval and ratio schedules (Morse, 1966). Yet response rate increased only with the smaller ratios, thereby indicat-
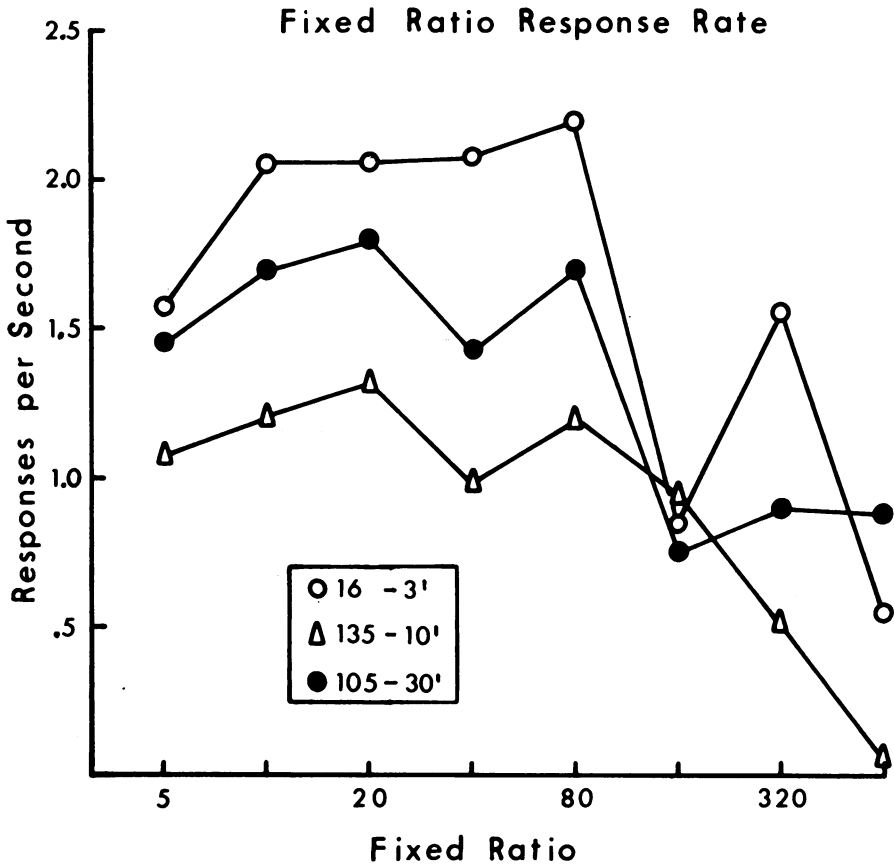
Fixed Ratio Response Rate

Fig. 4. Response rate in the FR period of the tandem FI FR schedules.

ing that rate cannot be the simple outcome of the IRTs that happened to be followed by the reinforcer. Preferential reinforcement of shorter or longer terminal IRTs cannot account for output with different FR schedules when the same IRT is preferentially reinforced but output changes.

Reinforcement frequency (the reciprocal of interreinforcer interval) has been shown to influence response rate in interval schedules (Catania & Reynolds, 1968; Herrnstein, 1970). The generally widely accepted rule is that as the interreinforcer interval increases, response rate decreases. Yet, in the present study, small increases in interreinforcer interval were correlated with elevated rate. A monotonic relation between interreinforcer interval and performance held only for postreinforcement pause duration and for the descending limb of the bitonic output function.

EXPERIMENT 2: CONJUNCTIVE FI FR SCHEDULES

With a conjunctive FI FR schedule, the reinforcer occurs as soon as both the interval and the ratio requirements are completed. The order of completion is irrelevant, in contrast to the tandem FI FR where the ratio must be executed after the interval requirement has been satisfied. With the conjunctive schedule, if the ratio requirement has been met before the interval times out, the first response after the interval lapses produces the reinforcer. If the interval requirement is met first, the reinforcer follows completion of the ratio. No exteroceptive event signals when a component requirement has been completed.

Several experiments have selected one value of ratio and interval in conjunctive FI FR

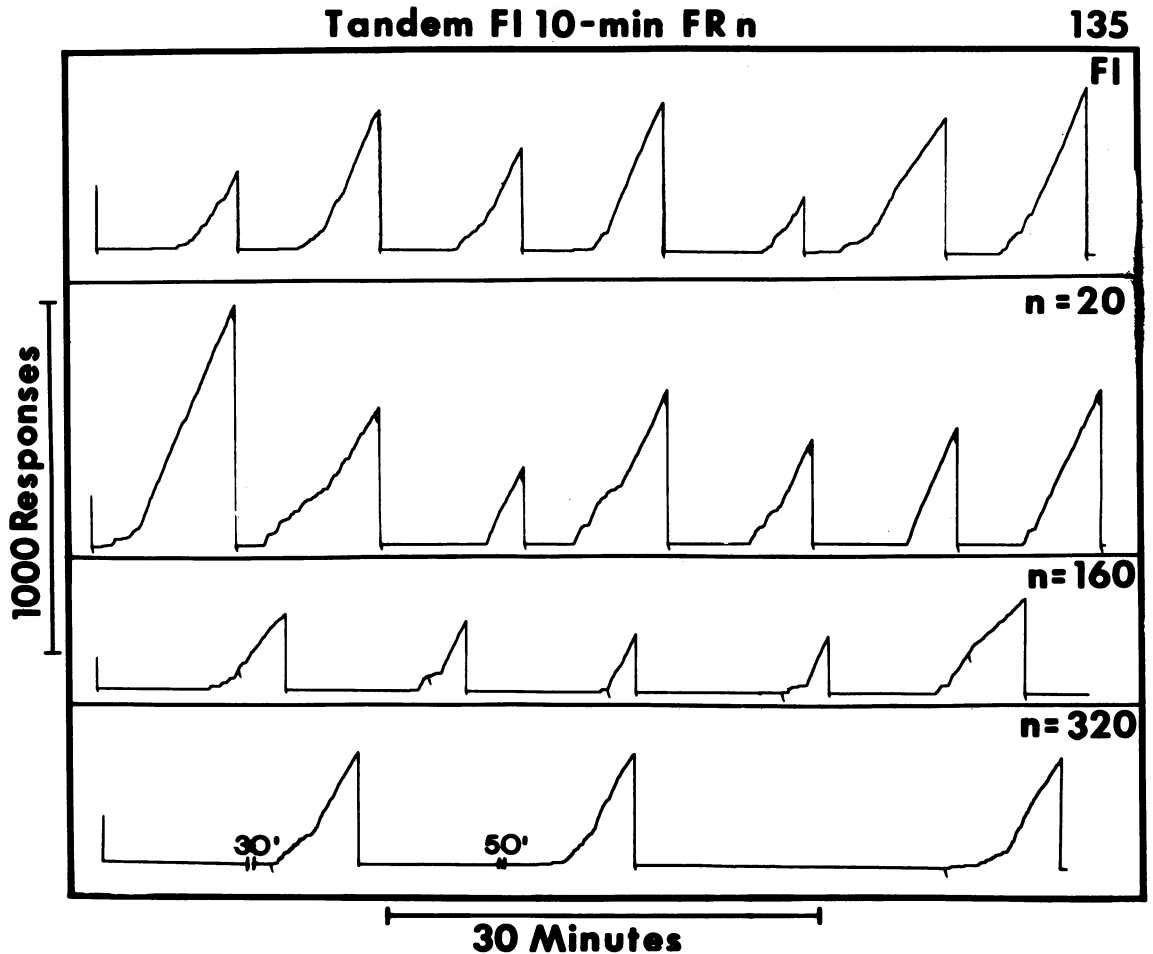## Tandem FI 10-min FR n
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135
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Fig. 5. Representative cumulative records for the tandem FI FR schedules. The response pen offset at completion of the FI requirement and reset after each food presentation. Numerals above the breaks in the records indicate elapsed time (in min) with no responses.

schedules to study response patterning, stimulus, or drug effects (e.g., Barrett, 1975), but Herrnstein and Morse's (1958) is the only parametric study. They varied FR size while keeping the FI constant at 15 min. Output during the FI period decreased monotonically as the ratio requirement was increased. This finding was provocative in that it indicated that any demands on output beyond the single response required by the FI decreased responding, and it led to a negative feedback theory of output control (Herrnstein & Morse, 1958; Zeiler, 1977), a theory closely related to Skinner's (1938) concept of the reflex reserve. According to these views, the current strength of a response is inversely related to the number of responses emitted previously. The data from conjunctive FI FR schedules fit so nicely be-

cause they implied that the conjunctive FI FR schedule reduced output relative to simple FI by setting a limit on how few responses could occur and thereby also limited response strength. These theories as general explanations of output have been reviewed elsewhere (Zeiler, 1979) and will not be discussed further here beyond saying that they are not adequate to most of the relevant data. Their major unique line of support is Herrnstein and Morse's results, although Herrnstein (1970) offered an alternative explanation in terms of decreasing reinforcement frequency.

Herrnstein and Morse's data imply a basic difference between conjunctive FI FR schedules and other arrangements involving joint time and response requirements. As seen in Experiment 1, tandem FI FR schedules pro-
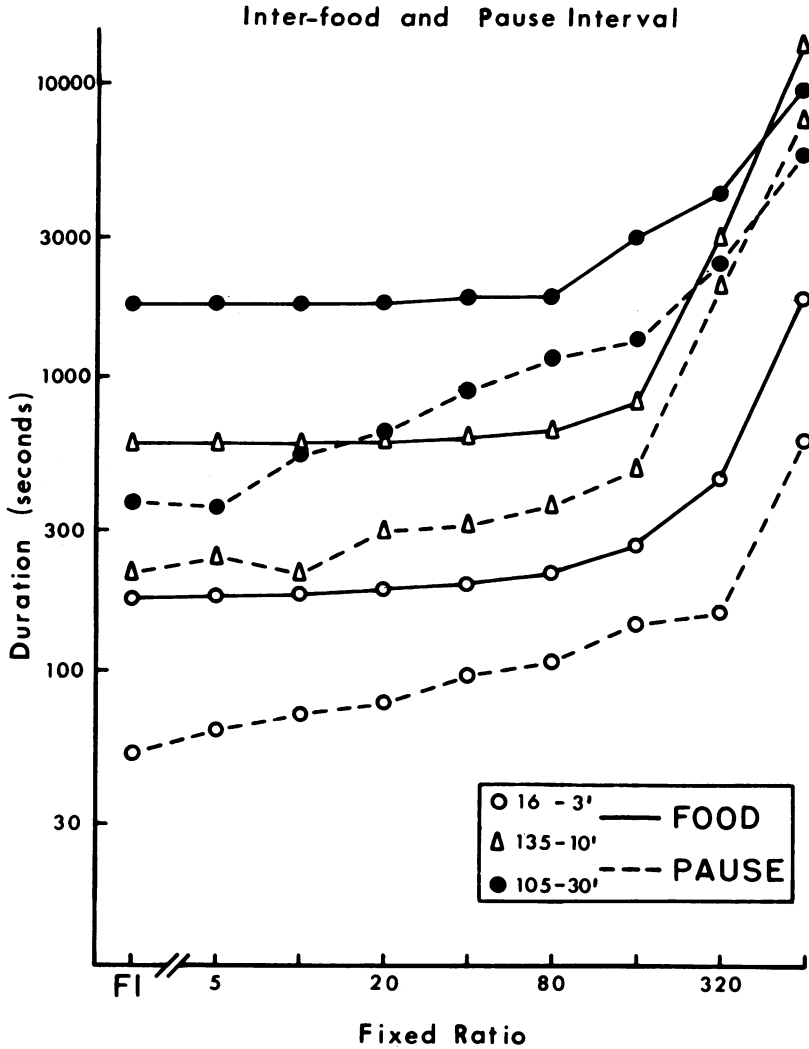
Fig. 6. Interfood interval (solid lines) and pause duration (dashed lines) for each bird with the tandem FI FR schedule.

duced both increases and decreases in output depending on the size of the FR, with changes not well correlated with reinforcement frequency. Also, ratio requirements have been manipulated in conjunctive FT FR schedules (Zeiler, 1976). This arrangement differs from conjunctive FI FR in eliminating the single response requirement at the end of the interval; the time-based component simply ends when the specified time period has elapsed. This schedule generated functions much like those of the tandem FI FR schedules. As the ratio requirement was increased, output first increased and then decreased.

In short, Herrnstein and Morse's (1958) re-

sults alone show monotonically decreasing output with ratios added to fixed intervals. Given the historical theoretical importance of these results, we decided to conduct another parametric analysis of the conjunctive FI FR schedule. As in Experiment 1, the size of the FI was varied between subjects, and size of the FR was manipulated within subjects.

METHOD

Subjects

Three White Carneaux pigeons were maintained at 80% of their free-feeding weights. Birds 1 and 42 had prior experience with a
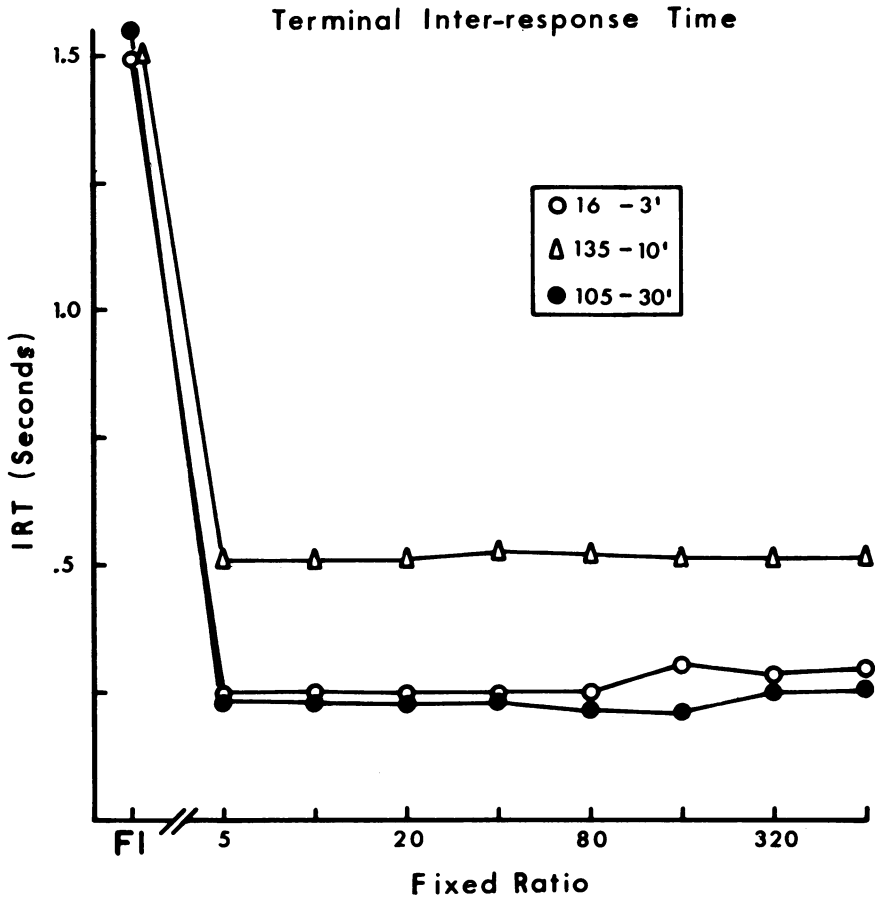
Fig. 7. Median terminal interresponse time (the IRT followed by food presentation) with the tandem FI FR schedules.

variety of reinforcement schedules, and Bird 137 was experimentally naive.

Apparatus

The chamber was like that of Experiment 1, with the exception of lighting. The response key could be transilluminated by two 7-W blue lamps, and a GE 25T10/1F lamp in series with a 300-ohm resistor, mounted on the upper right hand corner of the panel, provided general illumination except during the 4-sec feeder cycles.

Procedure

Table 3 shows the sequence of conditions. The FI value was 30, 10, and 5 min for Birds 1, 42, and 137 respectively. After exposure to a simple FI schedule, the conjunctive FI FR schedule was imposed in ascending order of ratios, beginning with FR 25 and ending with

FR 300. The ratio then was progressively decreased back to FR 25. Then, an ascending series of ratios was studied once again, this time with each conjunctive schedule separated by exposure to the simple FI. The final ratio value was 300 for Bird 1 and 400 for Birds 42 and 137. Each condition lasted for 20 sessions.

Sessions were conducted 5 days per week. Each involved 10 food presentations, the first occurring at session onset and the others according to the prevailing schedule. In the one schedule where responding was not maintained (conjunctive FI 30-min FR 300 for Bird 1), sessions ended after 15 hr.

RESULTS

The data of the last nine sessions of each exposure to a given schedule were combined in the following analyses. Means and standard deviations were taken over 9 to 72 sessions,

Table 3

Sequence of Conditions: Experiment 2

Conditions	Schedule
1	Simple FI
2	Conjunctive FI FR 25
3	Conjunctive FI FR 50
4	Conjunctive FI FR 100
5	Conjunctive FI FR 150
6	Conjunctive FI FR 200
7	Conjunctive FI FR 300
8	Conjunctive FI FR 150
9	Conjunctive FI FR 100
10	Conjunctive FI FR 50
11	Conjunctive FI FR 25
12	Simple FI
13	Conjunctive FI FR 100
14	Simple FI
15	Conjunctive FI FR 25
16	Simple FI
17	Conjunctive FI FR 50
18	Simple FI
19	Conjunctive FI FR 100
20	Simple FI
21	Conjunctive FI FR 150
22	Simple FI
23	Conjunctive FI FR 200
24	Simple FI
25	Conjunctive FI FR 300
26	Simple FI
27	Conjunctive FI FR 400 (Birds 42, 137)

depending on the number of exposures to each particular schedule. These means were representative of those for each exposure because no orderly differences emerged. Figure 8 shows that overall response rate increased and then decreased as a function of ratio size, peaking at FR 50 or FR 100 for all three birds. Table 4 shows that variability occurred in all conditions; these effects resembled those of Experiment 1.

Figure 9 shows the average number of responses emitted during the FI component. With each increase in ratio size up to FR 100, output was increased relative to FI: The conjunctive FI FR 100 schedule generated from 1.3- to 1.7-fold more responses during the FI period than did the simple FI schedule. With ratios larger than FR 150, output declined for all birds.

Figure 10 shows response rate after the first response. As in Experiment 1, this running rate varied with FR size and showed the bitonic function that also characterized overall rate and responses per interval. The main differences between running and overall rate in

the present experiment were that the functions peaked at different ratios for Bird 137, and running rate increased while overall rate decreased at the largest ratios for Birds 42 and 137.

Another comparison of output in the simple FI and the conjunctive schedules was how often the number of responses specified by the ratio requirement were emitted during the interval. In Conditions 14 through 27, the simple FI schedule preceded exposure to each of the conjunctive schedules. During each FI schedule condition, a counter tabulated the number of times that the number of responses emitted in the interval failed to match or exceed the FR requirement to be imposed in the next conjunctive schedule. During the conjunctive schedules, this same counter indicated the number of times that the ratio requirement was met after the interval component had been completed. Figure 11 shows that the conjunctive schedules always decreased the percentage of intervals in which output failed to exceed the level specified by the ratio. This measure of output indicated that the conjunctive schedules increased responding over the level supported by the simple FI schedule even when overall rate, average responses per interval, and running rate were declining.

The cumulative records of Figure 12 were generally representative of those for all of the birds. Variable output in successive interfood intervals characterized all conditions except those involving the highest valued fixed ratios. Responding usually was maintained once it began, although sometimes it was interrupted by short pauses. The prevailing pattern was a positively accelerated response rate, often followed by some rate decrease. With the largest FR values, the initial pause often extended well beyond the interval parameter value.

Figure 13 shows that initial pause duration and the interfood interval usually increased together as ratio size increased. The increase in the time between food presentations corresponded with the observation that with each higher ratio more food presentations followed completion of the ratio component (see Figure 11). No systematic data were available on terminal IRTs, although informal observations suggested that the IRT preceding food delivery seemed shorter when the ratio component was completed after the interval component.
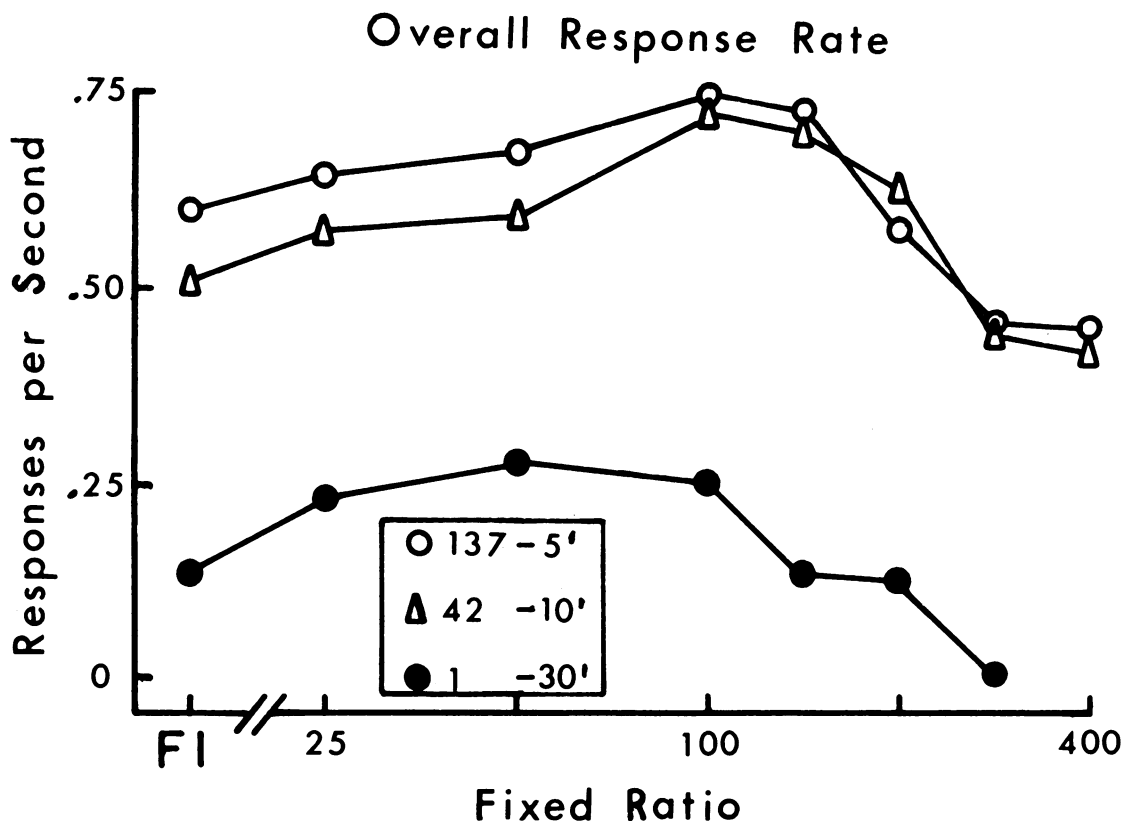
Overall Response Rate

Fig. 8. Overall response rate with the conjunctive FI FR schedules. The parameter value of the FI schedule appears next to each bird number.

DISCUSSION

The results corresponded with those of Experiment 1. With the conjunctive FI FR schedule, as with the tandem FI FR, output first increased and then decreased as the FR requirement was raised. In addition, the number of responses specified by the ratio always occurred more often during the interval component of the conjunctive schedule than during the simple FI schedule. The various changes in output occurred even though the frequency of reinforcement in time decreased monotonically with ratio size. Initial pause duration covaried closely with reinforcement frequency, but output did not.

The present results did not conform to those of Herrnstein and Morse (1958), who found consistent decline in output with each larger ratio. The reasons for the different results with the smaller ratios are not apparent. Although the present FI values did not correspond with their FI 15-min schedule, they were both

smaller and larger. Indeed, the present data imply that the size of the FI is as irrelevant to the overall effects of added ratios in conjunctive FI FR schedules as it is to those of tandem FI FR and conjunctive FT FR schedules. This might even be the case with shorter intervals where the schedule essentially would become equivalent to a simple fixed ratio.

Failures to replicate rarely are easily reconciled, and they raise the question of which results have the greater generality. One basis for judgment might be to evaluate which data fit best with others. Viewed from that context, Herrnstein and Morse's results are anomalous with respect to those obtained in other arrangements involving response requirements added to time-based schedules. In contrast, the present results fit well with those of tandem FI FR and conjunctive FT FR schedules in that all have found output to be a bitonic function of the size of the added ratio requirement. Furthermore, Marr (1979) has reported that a complex form of conjunctive FI FR

Table 4

Means and Standard Deviations: Experiment 2

	FI	Conjunctive FI FRn						
		n = 25	n = 50	n = 100	n = 150	n = 200	n = 300	n = 400
Bird 1								
Overall rate (resp/sec)	.2	.2	.3	.3	.2	.1		
	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)		
Responses per interval	282	408	480	500	267	156		
	(46)	(96)	(81)	(99)	(132)	(69)		
Running rate (resp/sec)	.2	.3	.4	.3	.2	.1		
				(Standard deviations not available)				
Interfood interval (sec)	1801	1803	1803	2030	2279	2429		
	(1)	(4)	(4)	(137)	(199)	(193)		
Pause (sec)	459	(450)	416	498	738	1032		
	(68)	(64)	(64)	(77)	(97)	(110)		
Bird 42								
Overall rate (resp/sec)	.5	.6	.6	.7	.7	.6	.5	.4
	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)
Responses per interval	308	340	357	452	427	345	203	138
	(47)	(29)	(35)	(60)	(59)	(45)	(45)	(63)
Running rate (resp/sec)	1.0	1.1	1.2	1.4	1.3	1.2	1.0	1.0
				(Standard deviations not available)				
Interfood interval (sec)	601	603	607	636	653	631	733	975
	(1)	(3)	(6)	(33)	(31)	(108)	(161)	(138)
Pause (sec)	285	283	296	302	(304)	(302)	393	567
	(45)	(49)	(46)	(51)	(50)	(43)	(60)	(68)
Bird 137								
Overall rate (resp/sec)	.6	.6	.7	.7	.7	.6	.5	.4
	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)	(.1)
Responses per interval	176	189	204	228	231	147	54	15
	(36)	(27)	(24)	(40)	(62)	(35)	(25)	(6)
Running rate (resp/sec)	1.2	1.3	1.4	1.6	1.6	1.4	.9	1.2
				(Standard deviations not available)				
Interfood interval (sec)	301	302	302	321	360	450	673	918
	(1)	(2)	(6)	(28)	(31)	(54)	(84)	(117)
Pause (sec)	152	(152)	(158)	170	196	267	330	587
	(32)	(35)	(34)	(43)	(41)	(57)	(66)	(59)

schedule showed the same basic shape of function as occurred here. The present results coordinate with all of these other findings, but Herrnstein and Morse's stand alone.

GENERAL DISCUSSION

Fixed-interval schedules represent a case of slightly constrained output. Only one response is required, and the schedule places no limit on how many responses more than one can occur although it does specify when that response will be effective. These schedules do, however, support many more responses on the average than can be maintained by fixed-ratio schedules that place stringent upper and lower limits on output. The present research showed that additional constraints on minimum responses with fixed-interval based schedules first enhanced and then reduced output whether measured in terms of either the number of responses during the fixed-interval period or overall response rate.

Although rigorous comparisons between the tandem and conjunctive schedules are precluded by the use of different subjects and other details of the design, some limited comparisons seem feasible. Figure 14 shows output in the tandem and conjunctive schedules relative to that in the simple FI schedule on the same-scaled axes. The conjunctive schedule produced maximum output at ratio values
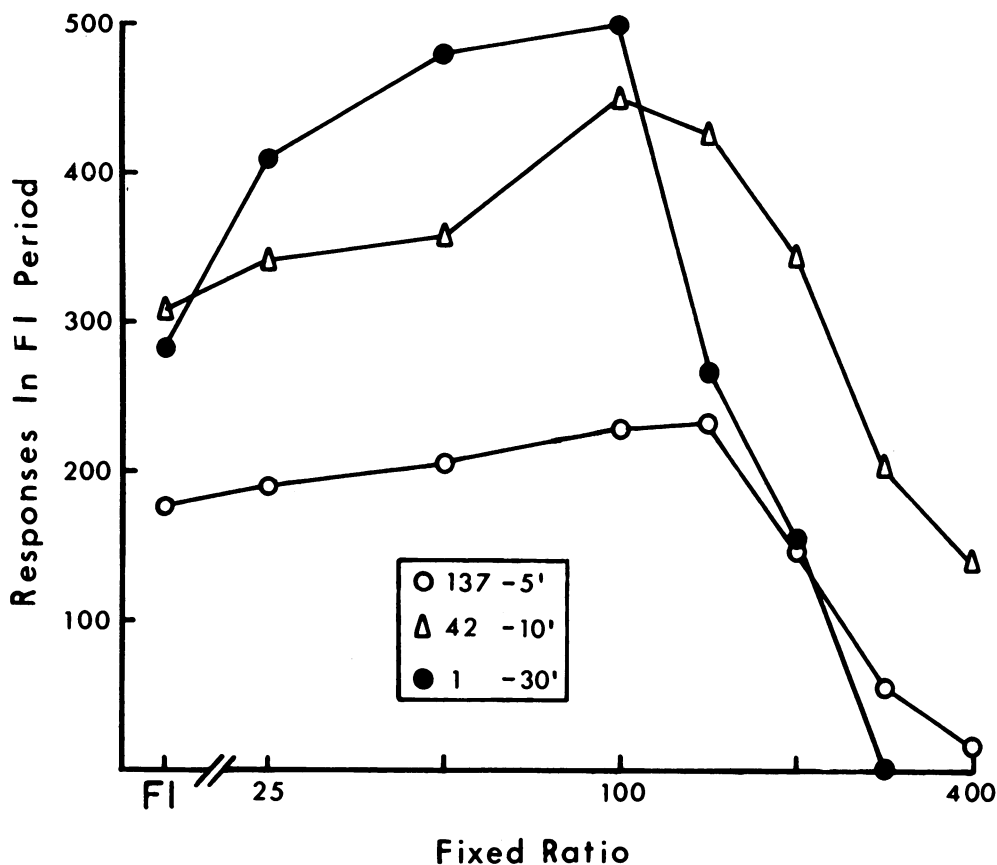
Fig. 9. Average number of responses in the FI period of the conjunctive FI FR schedules.

where the curves for the tandem schedules were declining. One possible reason for this difference is that the tandem schedule required that the entire ratio be completed after the interval but the conjunctive schedule allowed any part of the ratio to be executed during the interval. The conjunctive schedule is equivalent to a tandem schedule whenever the ratio requirement is completed after the end of the interval. However, unless very few responses occur during the interval, the responses remaining to be emitted are considerably fewer than the ratio value. Output functions peaking at different ratio values with the tandem and conjunctive schedules, then, should not be surprising because the conjunctive schedule would be equivalent to a tandem FI VR schedule where the VR value ranges from 0 to the FR response requirement. Given that large VR schedules maintain responding when same-valued FR schedules do not (Zeiler, 1979), higher rates with the conjunctive sched-

ule than with the tandem would seem to follow. In any event, the tandem and conjunctive schedules had generally similar effects on output. Even the magnitude of change relative to the simple FI seemed comparable (Figure 14). Consistent differences between the schedules appeared limited to the apparently steeper declining limbs of the conjunctive schedule functions shown in Figure 14.

Although the bitonic output functions generated by the tandem and conjunctive schedules could stem from different processes, their similar shapes imply a common source. No single process, whether an explicit independent variable or one arising from behavior, varied in correspondence with the output functions. The independent variable of fixed-ratio size increased continuously, but output first increased and then decreased, meaning that changes in response number requirements corresponded with changes in output over only one limb of the function. Obtained reinforce-
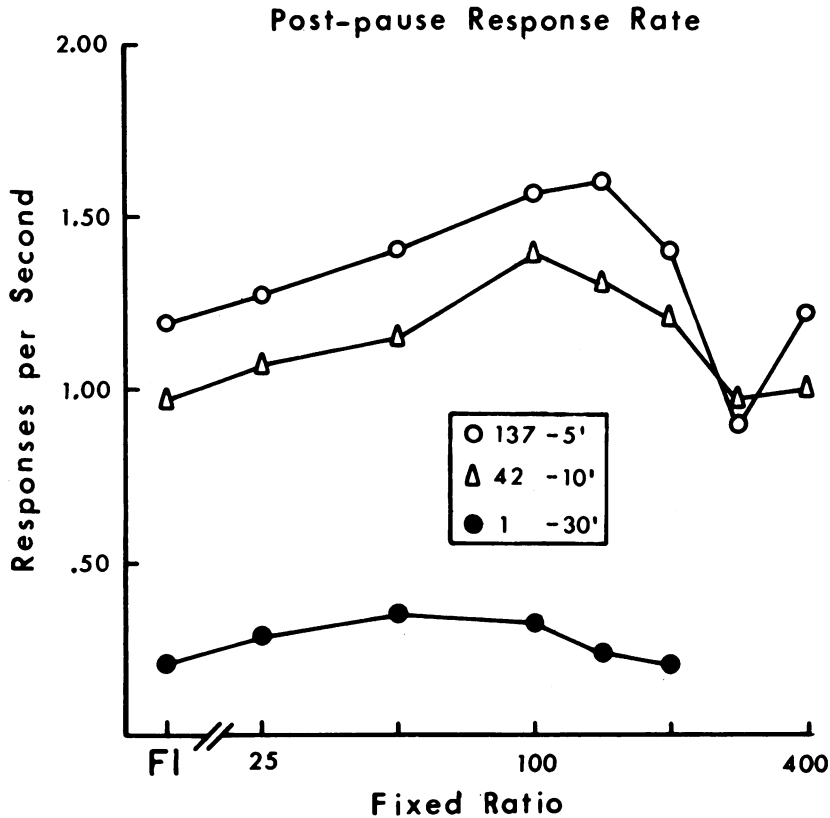
Post-pause Response Rate

Fig. 10. Response rate from the first to the last response (running rate) with the conjunctive FI FR schedules.

ment frequency was limited by fixed-interval size, but it also varied with the response requirement. With the tandem schedule, reinforcement frequency decreased with successively larger ratios; with the conjunctive schedule, reinforcement frequency first was unchanged and then decreased with each larger ratio. Such monotonic functions could not correspond to the bitonic output functions, although they did correlate reasonably well with changes in initial pause duration. The interresponse time (IRT) preceding food delivery was shorter with added ratio requirements than with the simple fixed-interval schedule. If output increases with shorter terminal IRTs, this would explain why added ratios produce higher rates than do interval schedules. However, the terminal IRT did not vary with ratio size, yet output continued to change in both directions. The implication is that at best only the very first part of the bitonic output functions could have depended on the IRT preceding reinforcement.

Inability to find changes in a single variable

that correspond to changes in output suggest the joint operation of two or more variables, one (or more) responsible for the increasing limb of the bitonic functions and the other (or others) for the decreasing limb. A two-process account stems from the possibility that output is an increasing function of both response requirement and reinforcement frequency. Successively larger response requirements increase output as long as reinforcement frequency is unchanged or is not decreased enough to exert a sufficiently strong counterbalancing or even overwhelming weakening effect. With still larger ratios, reinforcement frequency is lowered enough to subtract more from the tendency to respond than the increased number requirement adds, and output decreases. According to this hypothesis, bitonic output represents the interaction of response number and reinforcement frequency functions. It is a reinforcement theory analysis in that the two variables are viewed as parameters of the reinforcement operation that controls the strength of operant responding.
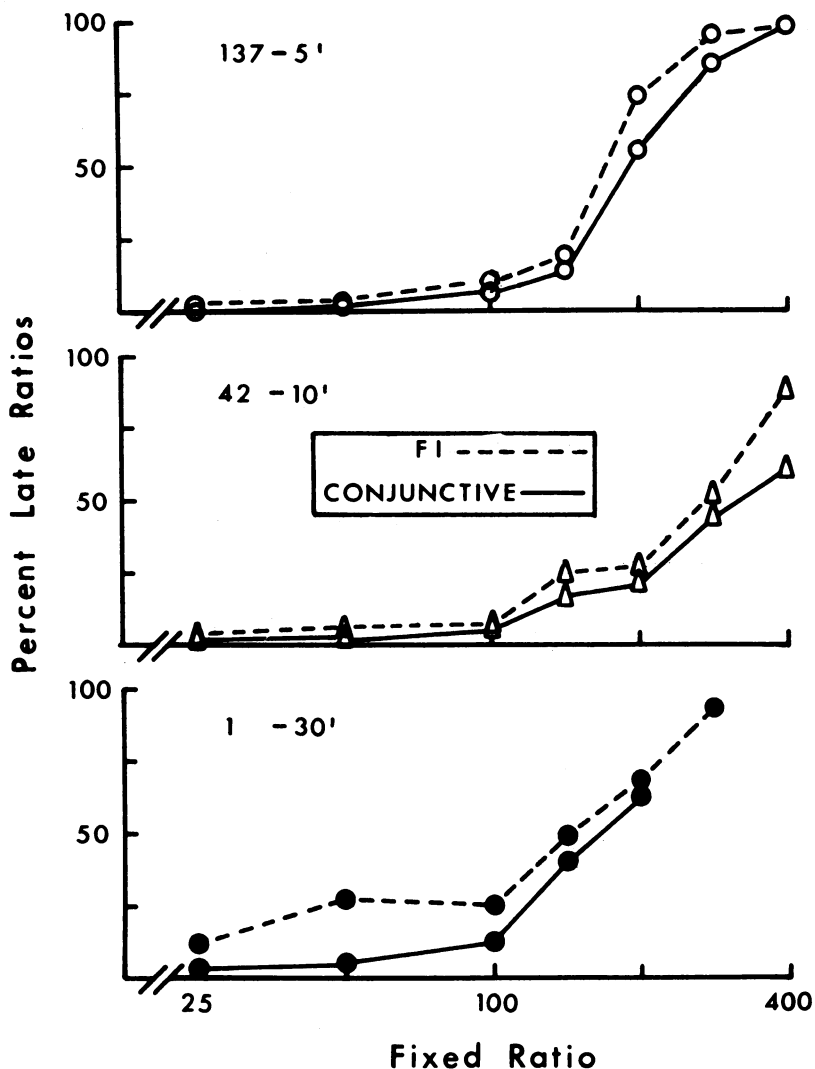
Fig. 11. Comparison of frequency of emission of *n* responses in the conjunctive FI FR and simple FI schedules. Points connected by solid lines show the percentage of instances in which the fixed-ratio requirement was met after the interval component was completed. This also is the percentage of times that food delivery immediately followed completion of the ratio. Points connected by dashed lines show the percentage of simple fixed intervals in which the number of responses required by the conjunctive schedule to be imposed next failed to occur.

A different type of theoretical model (Rachlin, 1978; Rachlin & Burkhard, 1978) specifically predicts that output with simple ratio schedules should be a bitonic function of instrumental response number requirements. At first glance, the present data appear to provide striking support for this model; however, further analysis raises the possibility that the model actually may not predict a bitonic function with tandem and conjunctive FI FR schedules. Some elaboration of the model is necessary to highlight the conceptual problem.

According to the model, behavior involves the allocation of time among various alternative responses. In the present case, where the only responses measured were key pecks and eating (approximated as access time to food), the alternative response classes are eating, pecking, and notpecking. The duration of each peck was short and approximately constant, and the duration of each eating bout was 3 or 4 sec. The time allocated to pecking, therefore, was the total number of pecks times a constant, that allocated to eating was the number of
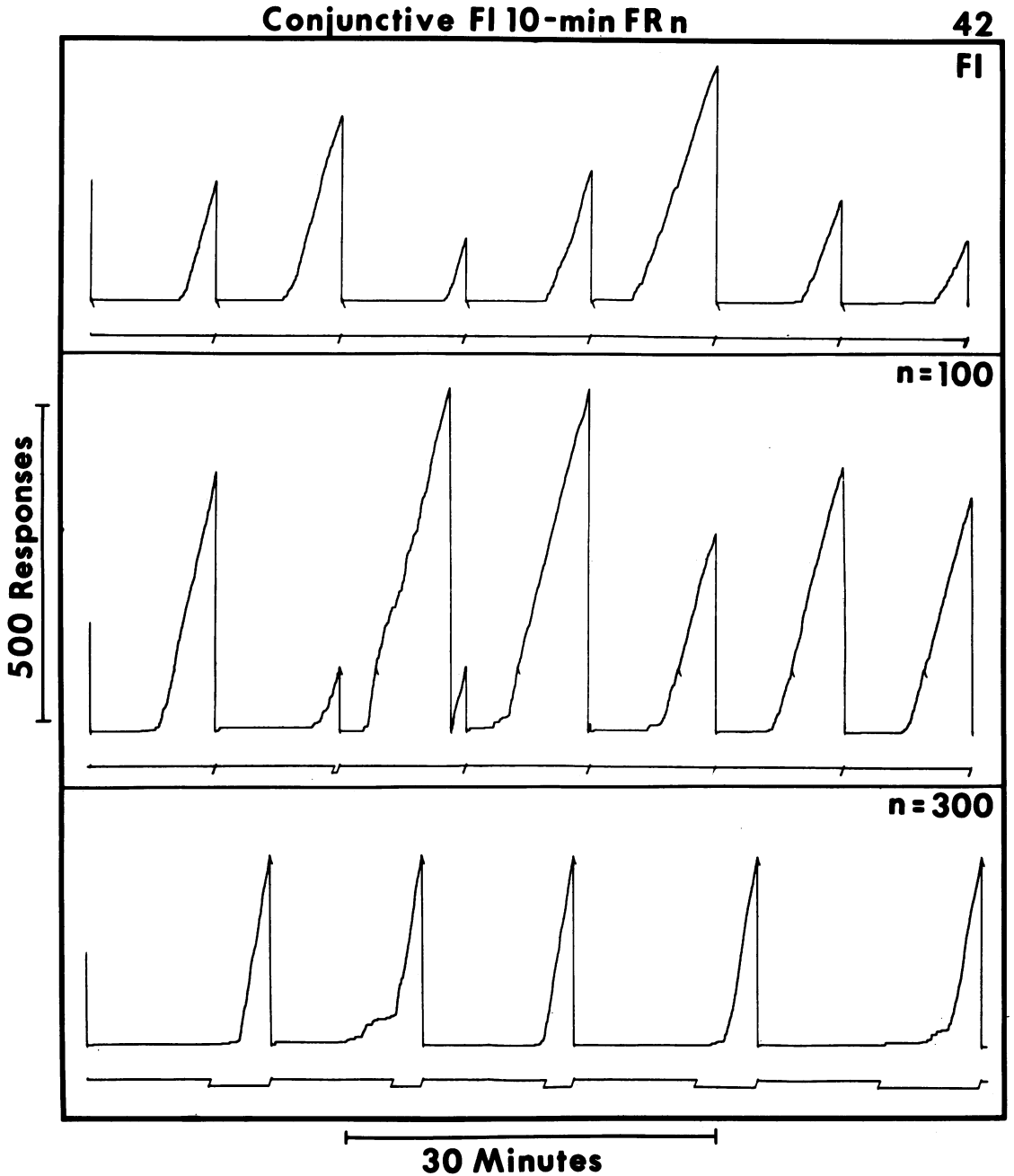
Fig. 12. Representative cumulative records for the conjunctive FI FR schedules. The response pen offset at completion of the FR requirement and reset after food presentation and after 550 responses. The event pen offset at completion of the FI requirement.

food deliveries times a constant, and that allocated to notpecking was the total session time minus the times allocated to pecking and eating. For the present situations, therefore, the function describing the time allocated to pecking has the same bitonic shape as that relating output to FR value.

According to the model, organisms allocate time among responses to maximize the value of the° set of responses, where value (V) is a function of the duration of each response in the set. When different distributions of activity among the component responses have the same value (an indifference surface), no one
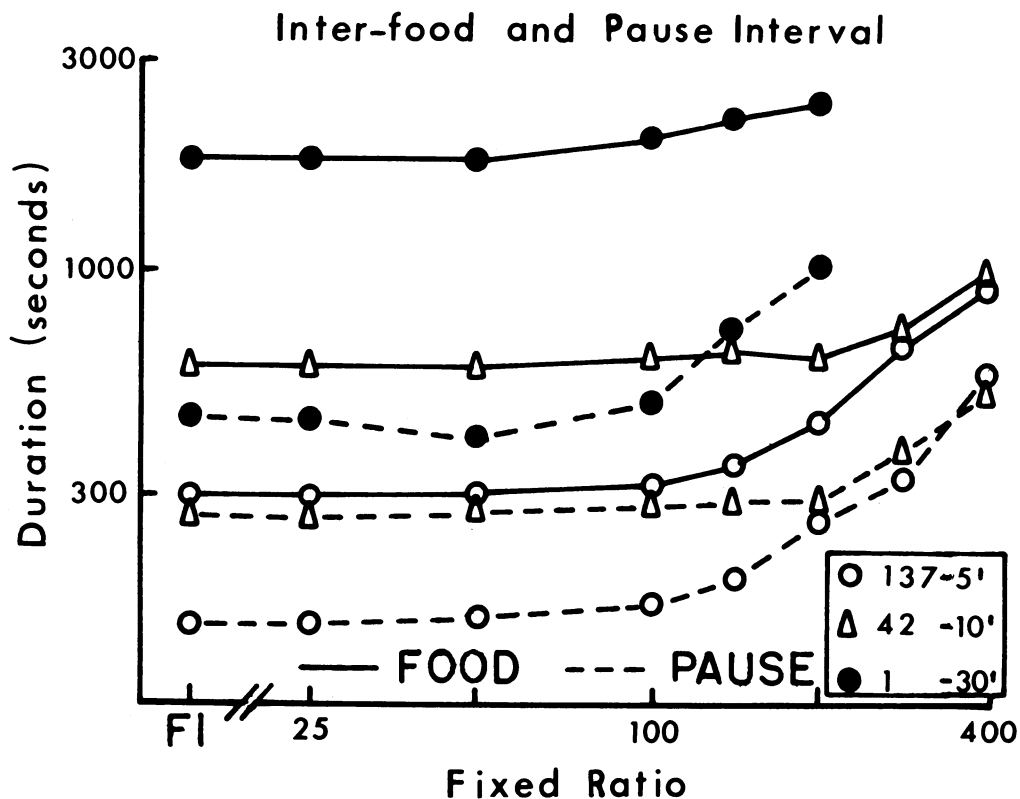
Fig. 13. Interfood interval (solid lines) and pause duration (dashed lines) for each bird with the conjunctive FI FR schedules.

distribution will be preferred over any of the others. However, when different distributions have different values, organisms will allocate responses to maximize value. The model imposes no a priori restriction on the form of the function relating a given indifference surface to the durations of the contingent (C), instrumental (I), and other (N) responses and three constants (a, b, and c). In special extreme cases, the function may be linear (e.g., $V = aC + bI + cN$); however, more generally it is conoid (conic-section function of three variables) or power ($V = C^a + I^b + N^c$). Power or hyperboloid functions lead to the prediction that the frequency of an instrumental response in a given period of time will be a bitonic function of a simple ratio requirement.

The question is whether the model predicts this same function with tandem and conjunctive schedules. Bitonic functions are predicted when access to the contingent (eating) response varies solely with instrumental response rate, as it does with simple ratio schedules. In the present cases, however, eating time was not simply determined by the rate of pecking but was radically restricted by the interval component of the tandem and conjunctive schedules. The proportion of time occupied by eating was not free to vary to any marked extent. For example, even a 3-min interval component meant that eating could not occupy more than .016 of total time, and a 30-min component limited eating to less than .002 of total time. How ratio schedules would yield bitonic output within this limitation is not obvious. Nor is it clear how added ratios would have output rise above the level maintained by the simple FI schedule as long as the FI restrictions continued. Clarification awaits further theoretical development. One possibility is to consider how the variability in output or time allocation allowed by the baseline FI schedule is restricted by added ratios. Although an FI schedule may produce high enough average output to satisfy an added ratio requirement, it does not do so in every interval. This type of restriction per-
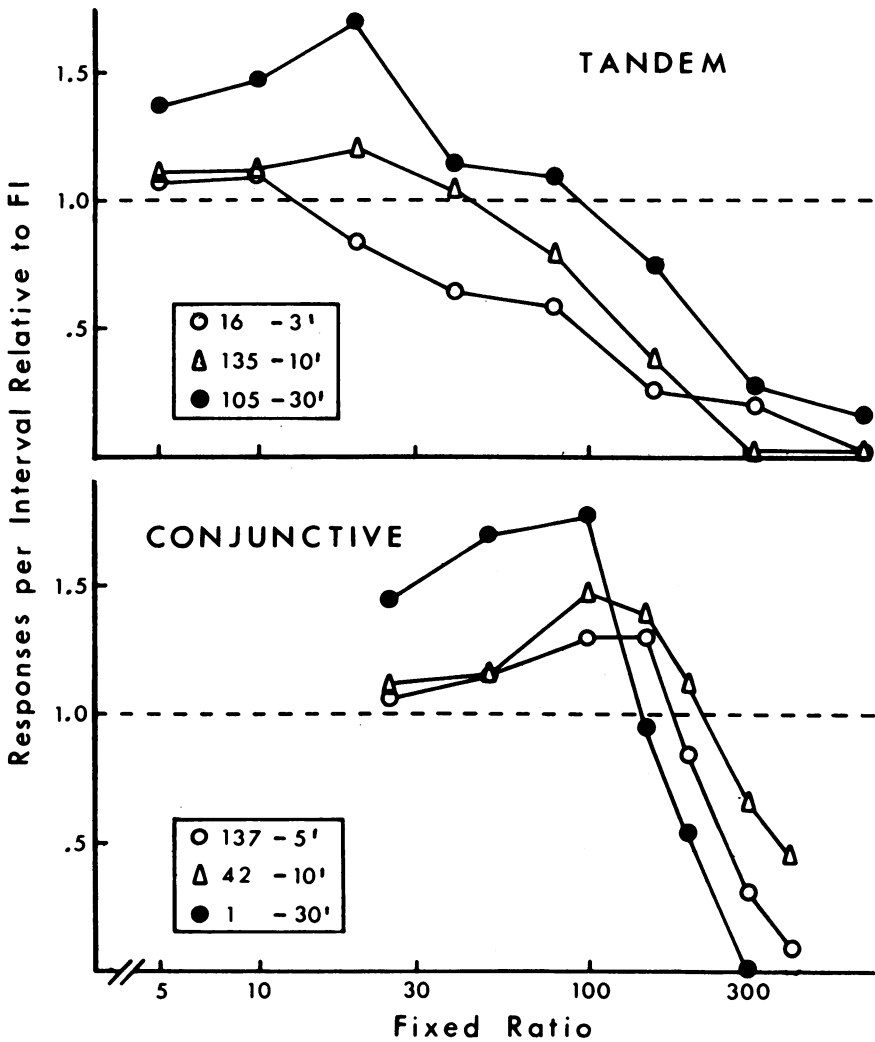
Fig. 14. Number of responses during the FI component of the tandem and conjunctive FI FR schedules relative to the number emitted during the simple FI schedule. The horizontal dashed lines show output during the simple FI schedules, and the function that would have resulted had responding not been altered by the tandem and conjunctive schedules.

haps influences the response allocation process by changing the form or level of the indifference surface.

The reinforcement theory hypothesis and Rachlin and Burkhard's (1978) economic or Allison's (1976) conservation models derive from fundamentally different conceptualizations of instrumental performance. Reinforcement theory views output as the manifestation of the strength of the instrumental response produced by parameters of reinforcement schedules. The economic and conservation approaches, in contrast, do not believe that response-reinforcer contingencies influence instrumental response strength. For example, the Rachlin and Burkhard model focuses on frequency of food presentation and the frequency of an instrumental response, but it does not consider the two as entering into a response-reinforcer relation. Instead, contingencies restrict how time can be apportioned among alternative responses, and the ensuing performance represents a new allocation that either maximizes the value (durations of a set of responses) or conserves a dimension common to the set of responses (e.g., overall energy output). The central issue is whether reinforcement is a fundamental process in operant be-

havior or is at best a label for a restricted segment of the overall function that describes changes in resource allocation when schedules constrain behavior.

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