TEMPORAL DISCRIMINATION AND A FREE-OPERANT PSYCHOPHYSICAL PROCEDURE

D. ALAN STUBBS

UNIVERSITY OF MAINE, ORONO

Pigeons were presented a series of keylight time periods (separated by blackouts) during which two response keys were lit, one by blue light and the other either by orange or green. Blue-key responses changed the color on the other key. Orange-key responses sometimes produced food during the first half of a time period; green-key responses sometimes produced food during the second half. In three experiments, the probability of a green-key response increased as a function of elapsed time. Experiment 1 compared performance when the duration of the keylight periods was varied across a wide range. Discrimination performance was similar across the range of durations. Experiment 2 varied both relative reinforcement rate and the local reinforcement rate for orange-key and green-key responses. These manipulations produced changes in response bias but not discrimination sensitivity. Experiment 3 varied the local temporal placement of reinforcers within time periods and demonstrated that choice behavior was affected by differential reinforcement at different points during the time periods. The results were consistent with previous research on duration discrimination that used psychophysical trials procedures.

Key words: temporal discrimination, psychophysics, response bias, Weber's law, local reinforcement rate, relative reinforcement rate, schedules, pigeons

---

Interest in the temporal discriminations of animals has led to experimental procedures similar to those used in human psychophysics (e.g. Church, Getty, & Lerner, 1976; Rilling, 1967; Snapper, Ramsay, & Schoenfeld, 1969; Stubbs, 1968). Stubbs, for example, trained pigeons on a psychophysical-trials procedure in which a stimulus was presented for one of ten durations ranging from 1 to 10 sec; then two response keys were lit and choice responses were reinforced, one response if the prior duration had been 1 to 5 sec and the alternate response if the duration had been 6 to 10 sec. An ogival function similar to those obtained in human psychophysical research described the relation between choice responding and stimulus duration.

Most psychophysical research has used trials procedures similar to the one just described. In contrast, the present series of experiments used a free-operant psychophysical procedure like that reported by Stubbs (1979). Stubbs presented pigeons with a series of keylight time periods with two response keys lit and operative for a maximum of 20 sec. Responses were reinforced intermittently with the restriction that left-key responses were reinforced during only the first half of a time period and right-key responses were reinforced during the second half. Probability of a right-key response increased as a function of stimulus duration, with the data being described by ogival functions.

There were several reasons for the present series of experiments. One reason was to find out whether the free-operant procedure yielded results similar to those of the trials procedure. Second, the free-operant procedure was designed, in part, to provide a procedure to bridge the gap between psychophysical trials procedures and free-operant schedules of reinforcement. The trials procedures are methodologically quite different from schedules, and this difference presents problems in trying to generalize from one set of data to the other. The free-operant procedure contains aspects of psychophysics and aspects of schedules and thus provides a procedure that is between the two that have been used to study temporal discrimination.

EXPERIMENT 1

Experiment 1 was designed to compare discrimination performance across a wide range of durations. Prior research using trials procedures has shown that discrimination sensitivity remains the same over different duration ranges (Church et al., 1976; Stubbs, 1968). The purpose was to see if similar results were obtained with the free-operant psychophysical procedure. Additionally, the range of durations was extended beyond those used in the previous experiments to compare discrimination performance across a wider and more complete range than has been done in the past.

METHOD

Subjects

Three adult male White Carneaux pigeons were maintained at 80% of their free-feeding weights. These pigeons had prior histories discriminating stimulus duration (Stubbs, 1968).

Apparatus

The experimental chamber was similar to that manufactured by Grason Stadler Co. Two response keys (Ralph Gerbrands Co.) were mounted horizontally 64 mm from center to center and centered above a feeder (Ralph Gerbrands Co.) The keys were transilluminated by differently colored lights. A force of approximately 0.15 N was required to operate the keys. The chamber contained a houselight and speaker through which white noise was delivered. Sessions were arranged by relay circuitry located in an adjacent room.

PROCEDURE

Sessions, conducted daily, lasted until a pigeon had received 50 food presentations. The left (main) key could be lit by orange or green light; the right (changeover) key could be lit by blue light.

Each session contained a series of time periods during which the keylights and houselight were lit. At the onset of each time period, the main key was orange and the changeover key blue. A response on the changeover key changed the color on the main key from orange to green, turned off the changeover-key light, and made the changeover key inoperative for the rest of that stimulus period.

Thus, only one changeover response was permitted per time period. Main-key responses produced food subject to the following restrictions. Main-key responses were reinforced intermittently in the presence of the orange keylight during the first half of the time period and in the presence of the green keylight during the second half. When, for example, the stimulus periods lasted 15 sec, orange-key responses produced food between 0 and 7.5 sec following stimulus onset whereas green-key responses produced food between 7.5 and 15 sec. If the response produced food, the time period was terminated and the animal received 3-sec access to food, during which the keylights and houselights were off and the feeder light was on. A 12-sec blackout followed food, and then a new stimulus period began. If a reinforcer was not produced during the stimulus period, a 15-sec blackout resulted, and then a new stimulus period began.

Time periods were divided into 10 equal time classes for scheduling and recording. Reinforcers were scheduled during 1 of the 10 time classes in each time period. When, for example, stimulus periods lasted a maximum of 15 sec, reinforcers were sometimes available between 0 and 1.5 sec (for orange-key responses), sometimes between 7.5 and 9 sec, etc. Reinforcers were scheduled irregularly and equally across the 10 time classes. A correction procedure was used: the stepping switch did not advance until a scheduled reinforcer was obtained; if the animal "missed" a reinforcer, a reinforcer was scheduled during the same class on the following stimulus period.

The durations to be discriminated were varied across conditions. The time periods used were as follows (in order of presentation): 0 to 15 sec, 0 to 50 sec, 0 to 75 sec, 0 to 7.5 sec, 0 to 15 sec, 0 to 200 sec, 0 to 150 sec, and 0 to 15 sec. The time classes were each 1.5 sec when the time periods were 0 to 15 sec, 5 sec when the time periods were 0 to 50 sec, 7.5 sec when the periods were 0 to 75 sec, etc. Each condition was in effect until there were no systematic changes in behavior for at least five sessions as determined by visual inspection. Conditions were in effect for an average of 40 sessions with a range of 25 to 53. When the 0- to 200-sec time period was instated, the time was gradually increased over the space of a week from a 0- to 15-sec range up

to the 0- to 200-sec range. Pigeon 7 was not exposed to the last four conditions due to illness.

RESULTS

Figure 1 shows probability data across different duration ranges, for both responses and time. Probability data were calculated separately for each time class: response data were calculated by dividing the number of green-key responses in each class by the total of responses emitted in that class; time data were calculated by dividing time spent in green by total time spent in that class. Figure 1 indicates that the probability functions were ogival and similar across conditions. The probability functions were quite similar for responses and time. In the first three time classes, the animals spent little time in green and emitted few green-key responses; in the next three, the amount of time and number of responses increased; and in the last four, the animals spent the majority of time in green and emitted mainly green-key responses.

Figure 2 provides information on variability and daily performance by presenting data for one pigeon on each of the last five sessions of three duration ranges, one short, one intermediate, and one long range. These are the data that were averaged for the ogives of Figure 1. Figure 2 shows that daily performance was quite orderly and that the mean data in Figure 1 were not the result of averaging out irregularities in daily performance. The data are similar to those in other conditions and those of the other two pigeons.

One aspect of the data deserves a comment. The procedure arranged reinforcement of orange-key responses during the first five time classes and green-key responses during the remaining five. Under this arrangement, one might expect that the animals would spend more time in orange and emit more orange-key responses during the first five classes, and spend more time in green and emit more green-key responses during the last five. However, Figures 1 and 2 show that probabilities increased above .5 before the sixth time class; in the fifth (and sometimes fourth) time class, the pigeons spent more time in green than in orange and emitted more green-key responses. These results indicate that the animals were shifting to green before the reinforcement consequences changed.

Figure 3 shows changeover data across conditions. All changeover responses (approximately 30 per session) were summed for the last five sessions of each condition; the total was divided into the number of changeover responses in the first time class, the second, the third, etc. Data from the different determinations of the 0- to 15-sec duration range were averaged. Figure 3 shows that the distributions of changeover responses were generally similar. Generally 70 to 80% of the changeover responses occurred during the first five time classes, with highest frequencies in the fourth and fifth time classes. Although the distributions were generally similar, the changeover responses tended to occur at shorter time classes, and the variability of the changeover distributions increased as the duration range was increased.

The changeover data agree with the probability data, but this agreement was expected since green-key responses and green-key time depended on the locations of the changeover response; time could not accumulate in green, and green-key responses could not be emitted until a changeover response had occurred.

Additional calculations permit a more detailed comparison of performance across conditions. Table 1 and the top portions of Figure 4 show calculations taken from the probability data (Figure 1). The times at which probabilities were .25, .50, and .75 were calculated by the linear interpolation method and used to provide measures often used in psychophysics (Guilford, 1954). The time at which the probability was .50 is similar to the "point of subjective equality" (PSE). The .75 and .25 points were used to find the "interval of uncertainty" (IU) by subtracting the smaller number from the larger; half of this number gives the difference threshold. The Weber fraction is $\Delta T / T$ where ΔT is the difference threshold and T is the PSE.

The bottom portions of Figure 4 show calculations on the changeover distribution: the mean time to changeover, the standard deviation, and the coefficient of variation.

Figure 4, presented in the manner of Gibbon (1977), shows the various measures as a function of duration range. One possibility was that the time estimate measures (PSEs and mean changeover times) and the variability measures (difference thresholds and standard deviations) would be proportional to stimulus
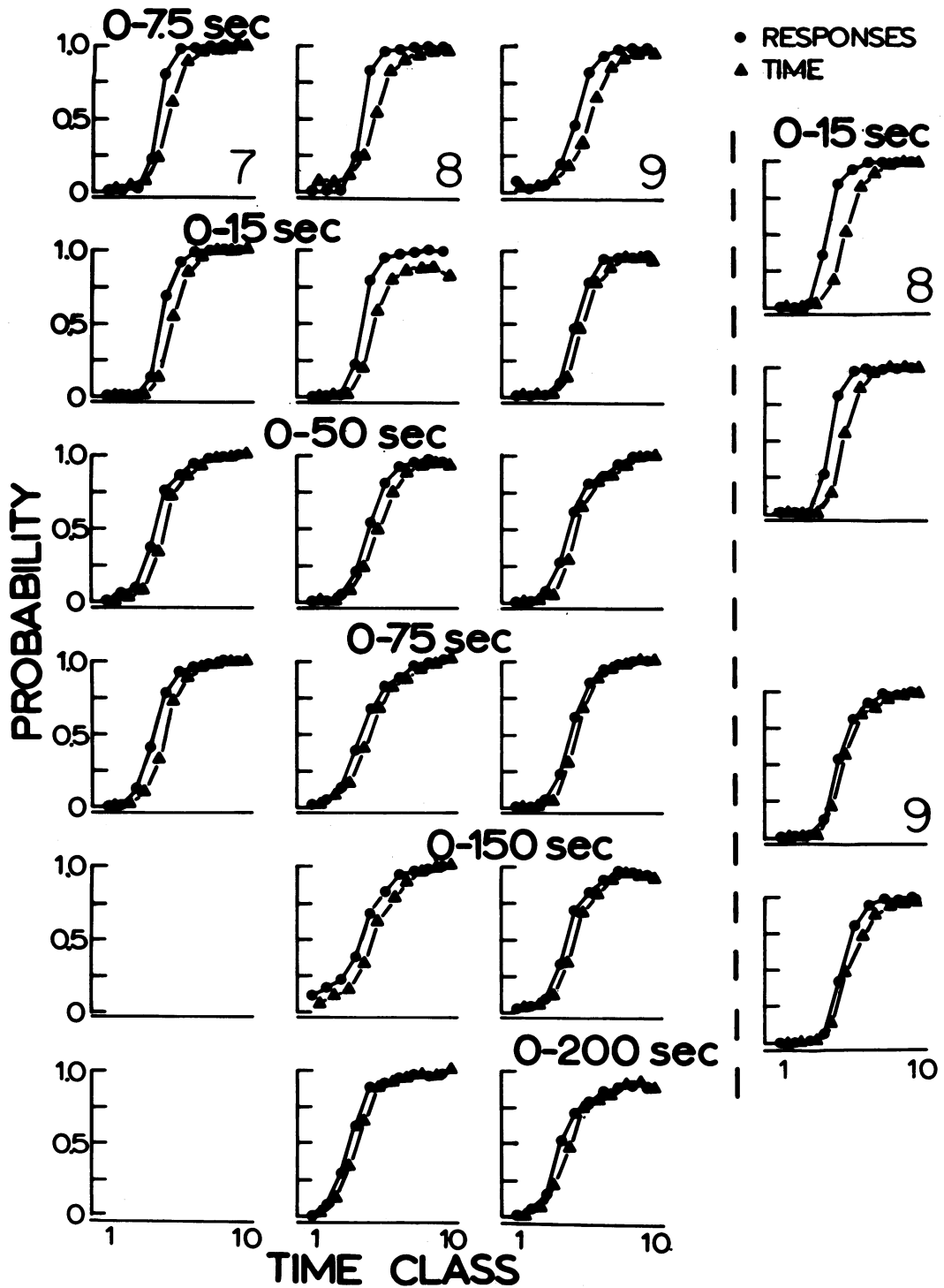
D. ALAN STUBBS

Fig. 1. Probability data across conditions when the durations range varied. Probability data are shown for responses (probability of a green-key response) and time (probability of time spent in green.) The time data have been displaced to the right to avoid overlap of circles and triangles. The data on the right show redetermination data when the duration range was from 0 to 15 sec. The data are means of the last five sessions.
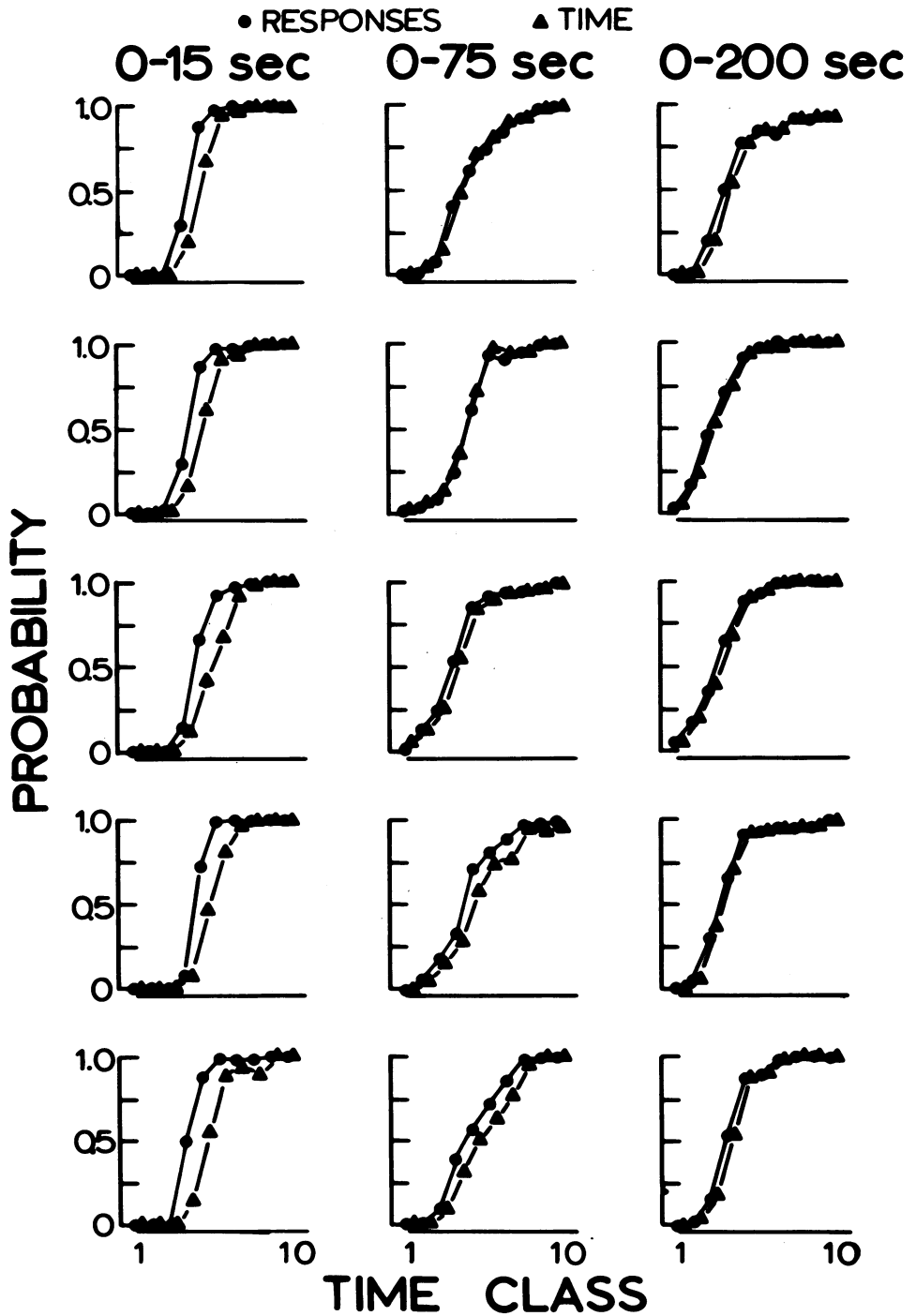
Fig. 2. Probability data for Pigeon 8 for three conditions. Different sections show daily performance for each of the last five sessions under a condition. Probability data are shown both for responses and time. The time data have been displaced to the right to avoid overlap of circles and triangles.

duration, such that the slopes of the lines would be 1.0 (Gibbon, 1977). However, the slopes were less than 1.0 for the time estimate data and greater than 1.0 for the variability data. A related possibility was that the Weber fractions and coefficient of variation measures
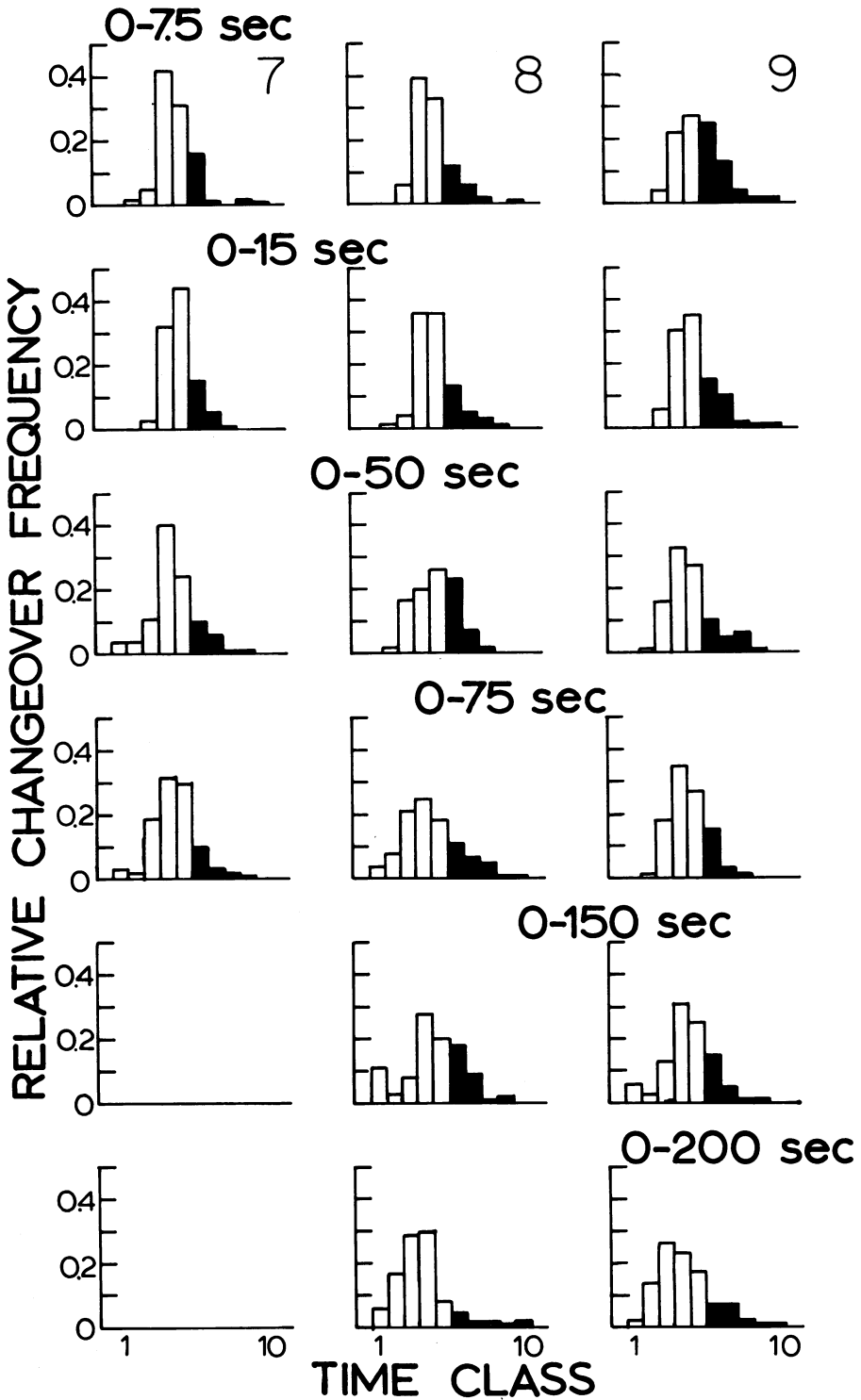
Fig. 3. The relative changeover frequency across the 10 time classes over conditions when the duration range varied. The data are unfilled for the first five classes, filled for the last five. The data were summed for the last five sessions of each condition. Different determinations (for Pigeons 8 and 9) were averaged together.
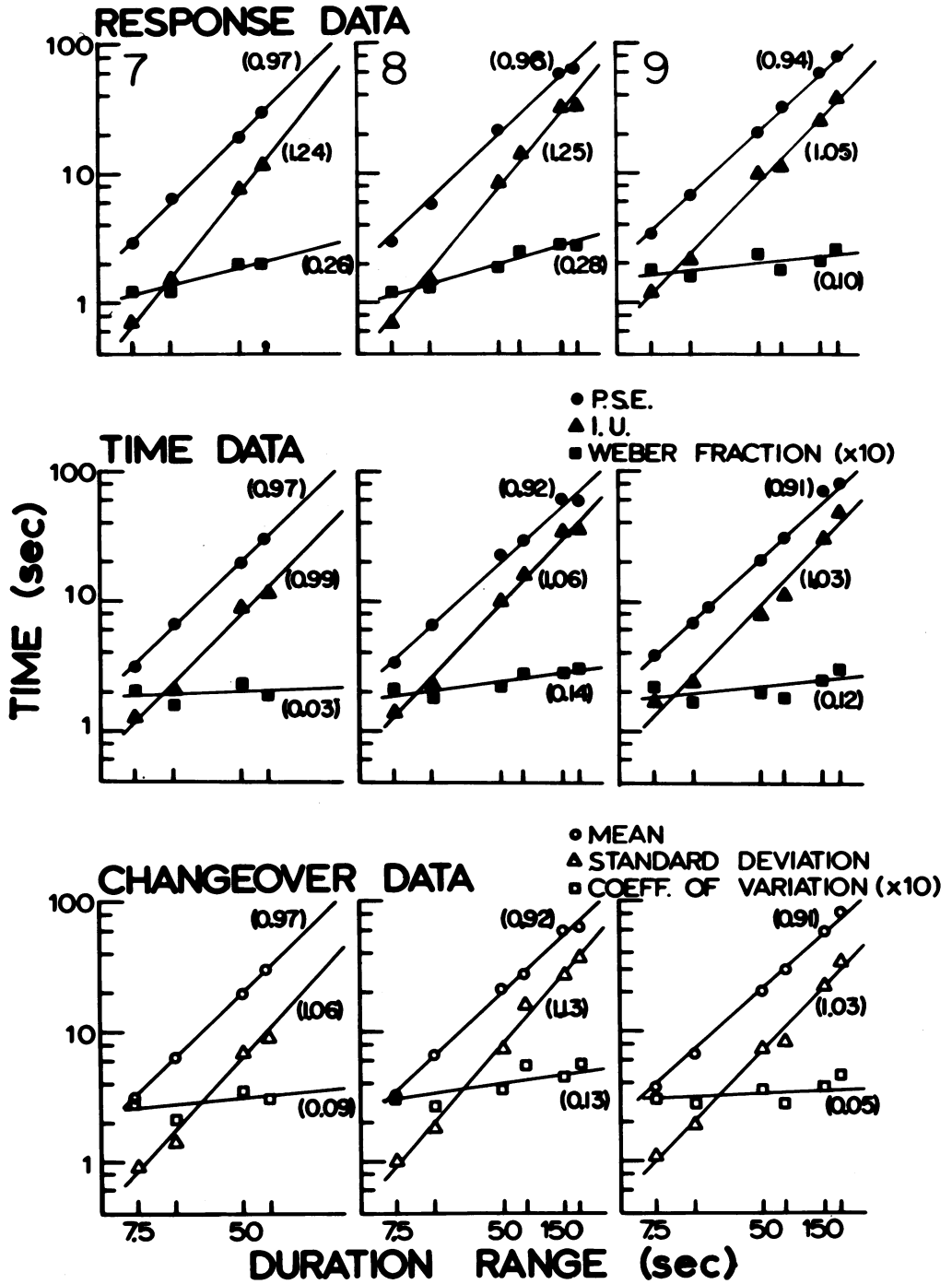
Fig. 4. Different measures plotted as a function of duration range (see text for details of the calculations of each measure). Both axes are logarithmic. The straight lines were fit to the points by the least squares method. The numbers in parentheses give the slopes of the lines. The points represent means of the last five sessions, with the means of different determinations of a condition averaged together.

would remain constant across conditions, indicating that Weber's law described the data (Gibbon, 1977). However, the slopes of the lines were positive in all cases, demonstrating an increase in the measures as duration range increased.
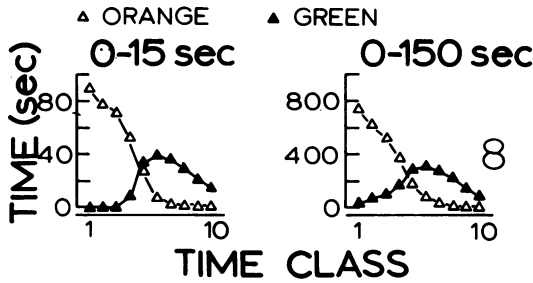
Fig. 5. Time spent in the different time classes for Pigeon 8. The data are separated into time spent in the presence of orange and green. The data are means of the last five sessions under two conditions.

Figure 5 shows the time spent in each time class for one pigeon under two conditions. The data were quite similar under other conditions and for the other pigeons. Total time (orange key plus green key) decreased across time classes since time periods terminated whenever a reinforcer was produced. The pigeons spent more time in the presence of orange during the first four time classes and green during the remaining time classes.

A pigeon could miss a scheduled reinforcer either by not responding during the time class or by responding exclusively in the presence of the inappropriate color. Typically, the pigeons missed approximately three to five reinforcers per session. Most of these were rein-

forcers scheduled during the fourth and fifth time classes.

DISCUSSION

A major finding was that discrimination performance generally was similar across a wide range of stimulus durations. The results are consistent with previous experiments on duration discrimination (Church et al., 1976; Stubbs, 1968) and extend the generality to a free-operant procedure and to durations five times longer than any used previously.

Although performance generally was similar, Figure 4 showed that discrimination sensitivity declined somewhat as the duration range increased. This decline in some ways parallels that observed with human subjects; several experiments have found that discrimination sensitivity declines as durations to be discriminated increase above 2 sec. In spite of the parallels, caution is in order before coming to conclusions about the pigeon results. As duration-to-be-discriminated increased, the rate of food delivery decreased; so it is possible that the changes in behavior were not due to discriminability at different durations but changes due to lowered reinforcement rate. Accuracy in discrimination and psychophysical procedures is influenced not just by the stimuli used but also by the contingencies and the ways they are arranged (e.g., Stubbs, 1968).

Table 1

"Point of subjective equality" and "interval of uncertainty" across conditions. Data are means of the last five sessions; numbers in parentheses are standard deviations.

Duration Range (sec)	Pigeon 7				Pigeon 8				Pigeon 9			
	RESP		TIME		RESP		TIME		RESP		TIME	
	PSE	IU	PSE	IU	PSE	IU	PSE	IU	PSE	IU	IU	PSE
0-7.5	2,9	.7	3.1	1.3	2.9	.7	3.3	1.4	3.4	1.2	3.8	1.7
	(.11)	(.11)	(.19)	(.30)	(.19)	(.10)	(.20)	(.23)	(.32)	(.34)	(.22)	(.54)
0-15	6.3	1.5	6.6	2.1	6.0	1.4	6.4	2.4	6.9	2.0	6.9	2.2
	(.22)	(.48)	(.28)	(.26)	(.34)	(.33)	(.24)	(.60)	(.63)	(.24)	(.57)	(.34)
0-15					5.7	1.6	6.8	2.4	6.8	2.2	5.8	2.4
					(.45)	(.12)	(.54)	(.48)	(.56)	(.38)	(.46)	(.46)
0-15					5.8	1.5	6.3	2.1	7.0	2.4	7.0	2.6
					(.42)	(.10)	(.48)	(.34)	(.50)	(1.0)	(.72)	(.57)
0-50	19	7.5	20	9.0	22	8.5	22	10	21	10	20	8.0
	(1.2)	(1.4)	(1.1)	(1.8)	(1.2)	(1.2)	(1.4)	(1.7)	(1.1)	(3.1)	(1.2)	(1.0)
0-75	28	11	30	11	28	14	29	16	32	11	31	11
	(2.1)	(2.0)	(1.9)	(2.2)	(2.0)	(3.8)	(3.4)	(4.8)	(2.9)	(2.2)	(3.2)	(1.8)
0-150					58	33	62	34	60	20	60	30
					(3.6)	(7.8)	(3.8)	(8.2)	(3.9)	(8.1)	(4.4)	(13)
0-200					62	34	60	36	72	38	72	50
					(6.4)	(8.8)	(9.2)	(5.8)	(7.6)	(16)	(4.0)	(13)

The results bear on research with temporally defined schedules and on Gibbon's (1977) scalar expectancy theory. Research with a variety of temporally defined schedules has demonstrated that a power function describes the relations between response output and schedule value. Catania (1970), for example, trained pigeons on a latency task in which responses were reinforced if they exceeded some minimum latency and found that latencies approximated the minimum reinforced latencies when the duration was varied. Catania observed that the relation was described by a power function, $T = kt^n$, where T is response latency, t the minimum reinforced latency, and k and n constants. Similar results have been obtained with differential-reinforcement-of-low-rate schedules (e.g., Catania, 1970), temporal differentiation procedures (e.g., Platt, 1979), and with more complex arrangements (DeCasper & Zeiler, 1977; Stubbs, Pliskoff, & Reid, 1978). A common finding in all of these situations is that the value of the exponent, n, is similar, with a value slightly less than 1. The findings, both of a power relation and exponents of less than 1, agree with the results of human psychophysics (Eisler, 1976; see, however, Platt, 1979). The present results agree. The PSE and changeover data of Figure 4 can be considered as time estimates and these data show power relations between performance and schedule value, with slopes (equivalent to the exponent of a power function) slightly below 1.0 in all cases.

Although there is close agreement between the different sets of data, Gibbon (1977) has offered a different analysis, casting doubt on the power function in animal research. Gibbon pointed out that it might be inappropriate to relate behavior to schedule value. If, for example, an animal is given a latency task in which the minimum reinforced latency is 5 sec, reinforced responses might be distributed around some time greater than 5 sec, say 5.4 sec. Gibbon argued that behavior should be related to the actual time to reinforcement, 5.4 sec, rather than the schedule value of 5 sec. He has reanalyzed the data of several experiments and obtained a linear relation when response output is related to obtained reinforcement times.

The data of Figure 4 were reanalyzed with Gibbon's point in mind. Observations revealed that the birds typically obtained a reinforcer within the first sec of a time class, and recordings showed that response rates approximated 1 response/sec across conditions. These bits of information suggested a reasonable estimate, that reinforcers were distributed around a time one half sec after a time class began. This estimate was used to establish a "functional cutoff," or point at which the contingencies functionally changed. When, for example, the 50-sec time period was used, the fifth time class ranged between 20 and 25 sec and the sixth between 25 and 30 sec. However, it would appear that orange-key responses were reinforced with a distribution around 20.5 sec and green-key responses around 25.5 sec. Accordingly, the cutoff would lie midway between, at 23 sec. When the different behavior measures were plotted against these estimated cutoff points rather than schedule value as in Figure 4, slopes of the straight-line functions approximated 1 (slopes of 1.02, 1.03, and 1.03 for Pigeon 7; 1.00, .96, and .96 for Pigeon 8; and .98, .95, and .95 for Pigeon 9 for response, time, and changeover data, respectively). The data agree with Gibbon since slopes of 1 indicate a linear rather than a power relation. The data in this and other respects support Gibbon's scalar expectancy theory.

EXPERIMENT 2

Relative reinforcement rate was varied in Experiment 2. Two considerations led to the procedure. First, contemporary psychophysical research has emphasized that some factors influence sensitivity while others influence response bias. Manipulation of "payoffs," in this case relative reinforcement rate, should influence response bias but not sensitivity. This variable has been studied in a trials procedure involving duration discrimination (Stubbs, 1976b), so present results could be compared with past. Second, Experiment 1 showed that the subjects tended to shift to green earlier than might be expected. The reinforcement scheduling changes were made to study the way in which reinforcement affected choice behavior and provide an explanation of the premature shift observed in the first experiment.

METHOD

Subjects

Three pigeons, maintained at 80% of their free-feeding weights, served. The three pigeons had prior experimental histories (Stubbs, 1968).

Apparatus

The apparatus was the same as in Experiment 1.

Procedure

The basic aspects of the procedure were the same as those of Experiment 1. For all conditions, the time period was 0 to 15 sec with orange-key responses producing food between 0 and 7.5 sec and green-key responses producing food between 7.5 and 15 sec. The first set of conditions manipulated the relative reinforcement rate. The conditions, in order of presentation, provided the following relative reinforcement rates for green-key responses: .50, .33, .67, .83, .17; then .17, .83, and .50. When, for example, relative reinforcement rate was .33, 33% of the reinforcers were scheduled for green-key responses and 67% for orange-key responses. As relative reinforcement rate varied, those reinforcers assigned to orange-key responses were evenly distributed between the five short time classes and those assigned to green-key responses were evenly distributed between the five long classes. Under the first five conditions, the changeover key was always on and functional during key-light periods. Thus, the animals could change back and forth from orange to green. Under the last three conditions only one changeover response was permitted during each time period as in Experiment 1.

Each condition was in effect until no systematic changes in behavior were observed for at least five sessions. The conditions were in effect for an average of 29 sessions, with a range of 17 to 51.

Finally, for 25 sessions, food was available irregularly during only 50% of the time periods. During the remainder, the time period simply lasted the maximum 15 sec, and then a blackout resulted. This condition was conducted to more nearly equalize exposure to short and long time classes. Pigeon 10 developed a tumor and was not exposed to this condition.

RESULTS

Figure 6 shows probability data for responses only; time measures were very similar and are not shown. Ogival functions obtained, but as relative reinforcement rate increased, the functions shifted to the left. When, for example, the relative reinforcement rate was .17, green-key probability was near zero for the first four time classes, then the functions rose steeply; in contrast, the probability was near zero for only the first two classes when the relative reinforcement rate was .83, then the probability functions increased. The equally steep slopes (see IU data in Table 2) across conditions suggested that the change in responding was a change in response bias not sensitivity (see Stubbs, 1968). Performance was similar whether the changeover key was always available or whether one changeover response was permitted in each time period.

Figure 7 shows changeover performance for those conditions where only one changeover was permitted. The distribution of changeover responses shifted to shorter time classes as the relative reinforcement rate for green-key responses increased. For example, Pigeon 11 emitted 56% of his changeovers in time classes 6 through 10 with the .17 rate, 39% with the .50 rate, and only 22% with the .83 rate. The results show that the animals changed from orange to green at an earlier time as the reinforcement rate for green-key responses increased.

Table 2 and Figure 8 show changes in various summary measures across conditions. Table 2 provides information on variability of performance.

Figure 8 relates three measures to relative reinforcement rate. The top portions show the time, expressed in terms of the 10 time classes rather than in terms of seconds, at which the probability of a green-key response was .50 (point of subjective equality). The time class decreased as relative reinforcement rate increased: the pigeons shifted to green sooner when green-key responses produced more reinforcers. Most of the points fell below 5.5, the value that would be expected if the animal's behavior was under the control of the time class at which reinforcement conse-
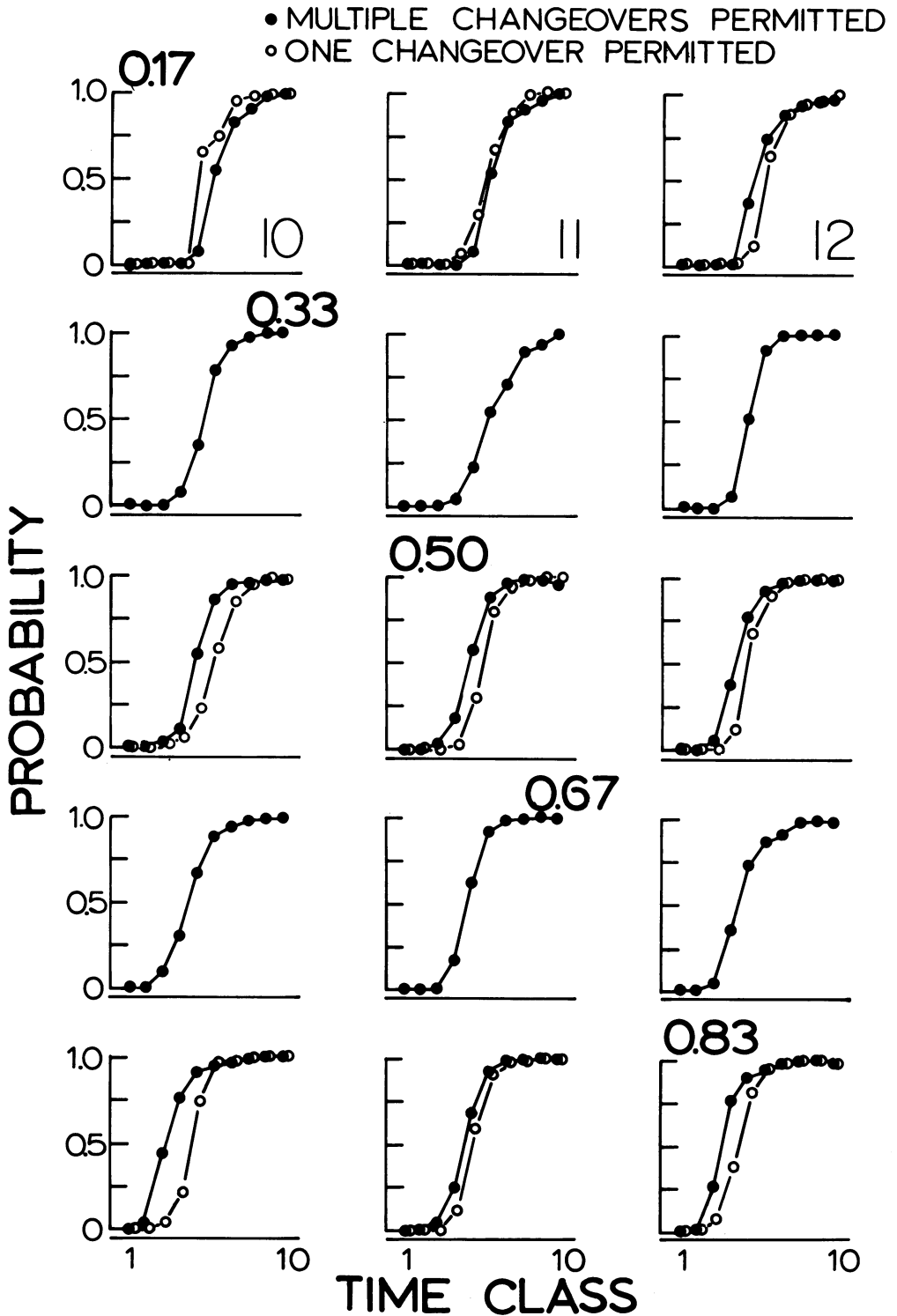
Fig. 6. Probability data across the 10 time classes as the relative reinforcement rate for green-key responses was changed. The data show probability of a green-key response when multiple changeovers or only one changeover could occur in each time period. The unfilled circles have been displaced to the right. The data are means of the last five sessions.
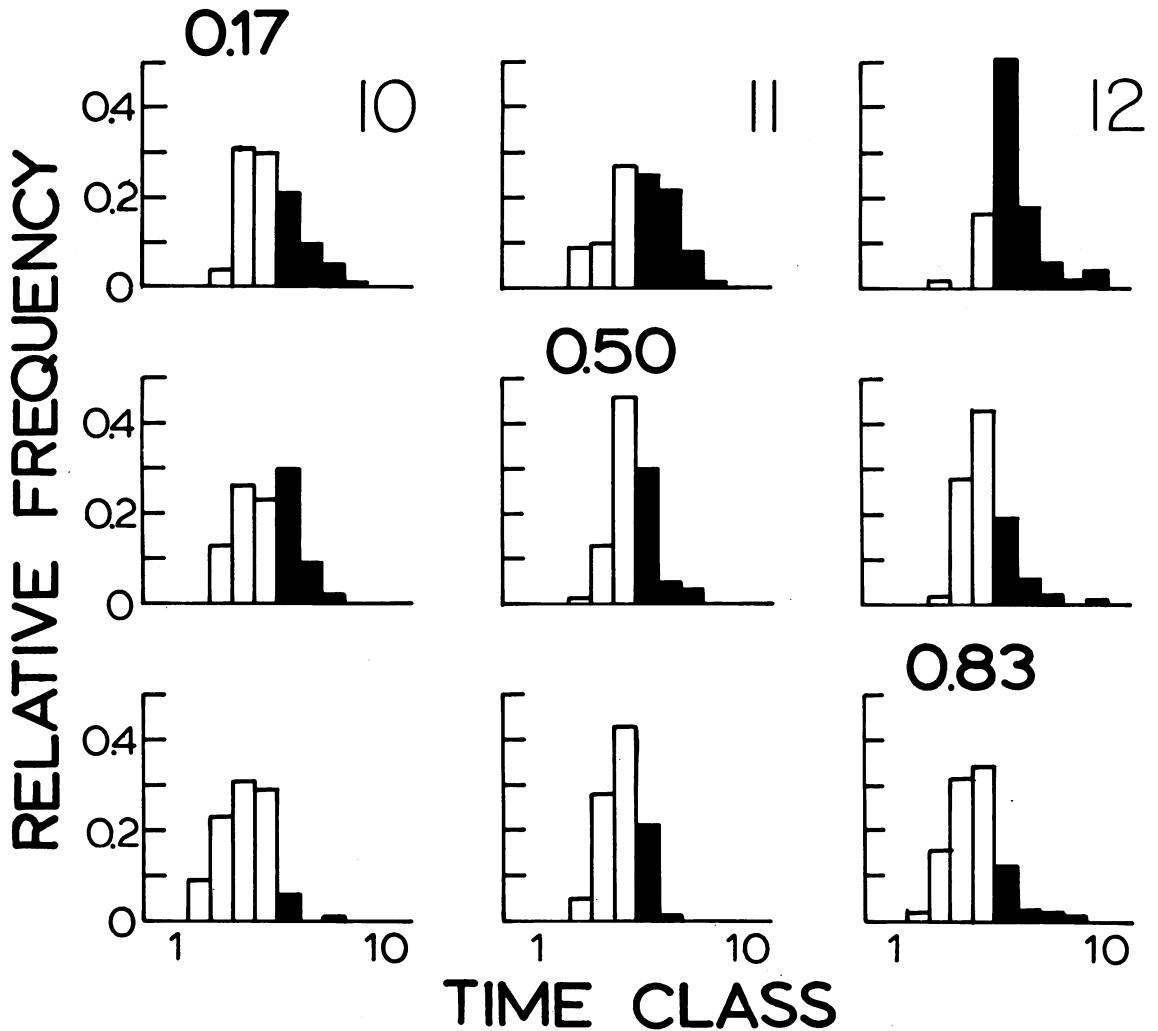
Fig. 7. Relative changeover frequency across the 10 time classes over conditions where the relative reinforcement rate for green-key responses varied. The bars are unfilled for the first five classes, filled for the second five. Only those conditions in which one changeover response was permitted are shown. The data are means of the last five sessions.

quences changed. Why did the pigeons tend to shift "too soon"? The bottom two portions help clarify the matter.

The middle portion shows the relative amount of time spent in green. The data were calculated simply by dividing the time spent in green by the total time spent in the presence of green and orange. Relative time spent in green increased as relative reinforcement rate increased, but the relative time spent in green never exceeded .5 except with the .83 relative reinforcement rate. These results are due to the procedure; the animals were exposed to the earlier time classes more often,

thus inflating the time spent in orange. The relatively small amount of green-key time suggests a difference in the local effects of reinforcement in orange and green. Consider the case where the overall relative reinforcement rate was .5. An equal number of reinforcers were produced by green-key and orange-key responses, but the pigeons spent much more time in the presence of orange. As a result, the local reinforcement rate (reinforcers in a color divided by time spent in the presence of that color) was higher in green since the animals obtained the same number of reinforcers as in orange but spent much less time. Although the

Table 2

"Point of subjective equality," "interval of uncertainty"—Relative time spent and relative local reinforcement rate. Date are means of the last five sessions and (in parentheses) standard deviations.

| | Responses | | Time | | | Rel. Local |
	PSE	IU	PSE	IU	Rel. Time	Rein. Rate
PIGEON 10						
17	8.7	2.0	8.0	2.4	.20	.45
	(.70)	(.39)	(.63)	(.94)	(.03)	(.05)
33	7.2	1.8	7.0	2.4	.36	.48
	(.72)	(.45)	(.63)	(.34)	(.04)	(.05)
50	6.9	2.1	6.9	2.7	.35	.65
	(.58)	(.45)	(.40)	(.44)	(.02)	(.02)
67	6.2	2.4	6.2	3.2	.45	.72
	(.36)	(.50)	(.75)	(.80)	(.04)	(.02)
83	4.0	2.1	4.0	2.8	.61	.77
	(.62)	(.40)	(.33)	(.81)	(.03)	(.02)
17	7.4	2.0	7.0	2.2	.34	.28
	(.72)	(.30)	(.36)	(.32)	(.04)	(.01)
50	8.0	2.6	6.8	3.0	.42	.59
	(.33)	(.60)	(.50)	(.48)	(.04)	(.05)
83	6.0	1.6	5.4	2.6	.54	.80
	(.33)	(.21)	(.24)	(.28)	(.04)	(.05)
PIGEON 11						
17	8.8	1.6	9.0	3.2	.13	.57
	(.91)	(.48)	(.87)	(.81)	(.02)	(.04)
33	8.1	3.0	8.7	3.8	.23	.62
	(.66)	(.99)	(1.0)	(1.0)	(.04)	(.04)
50	6.4	2.1	6.6	2.4	.34	.66
	(.39)	(.32)	(.39)	(.28)	(.03)	(.03)
67	6.3	1.8	6.3	2.1	.40	.77
	(.28)	(.42)	(.33)	(.24)	(.01)	(.02)
83	6.2	1.8	6.2	2.2	.42	.87
	(.34)	(.34)	(.45)	(.40)	(.04)	(.02)
17	7.6	2.2	8.1	2.6	.20	.46
	(.90)	(.48)	(.98)	(1.1)	(.02)	(.03)
50	7.4	1.6	7.4	1.8	.31	.72
	(.24)	(.30)	(.16)	(.36)	(.02)	(.02)
83	6.4	1.8	6.6	2.1	.39	.89
	(.36)	(.22)	(.48)	(.98)	(.03)	(.01)
50*	7.5	2.7	7.2	2.1	.47	.52
	(.36)	(1.2)	(.26)	(.22)	(.05)	(.04)
PIGEON 12						
17	7.4	2.2	8.2	2.6	.19	.42
	(.68)	(.96)	(.94)	(1.3)	(.07)	(.06)
33	6.8	1.5	7.0	2.0	.29	.55
	(.54)	(.24)	(.63)	(.24)	(.03)	(.05)
50	5.7	2.0	6.3	2.7	.36	.64
	(.34)	(.26)	(.46)	(.50)	(.03)	(.03)
67	5.7	2.2	6.4	3.2	.39	.74
	(.62)	(.33)	(1.0)	(.51)	(.06)	(.06)
83	4.5	1.8	4.8	2.6	.52	.82
	(.52)	(.44)	(.57)	(.84)	(.06)	(.03)
17	8.0	1.8	8.6	1.8	.16	.52
	(.42)	(.92)	(.72)	(.56)	(.04)	(.08)
50	6.6	1.5	6.9	2.1	.35	.63
	(.54)	(.34)	(.46)	(.30)	(.04)	(.05)
83	5.7	2.0	6.2	2.6	.43	.87
	(.33)	(.39)	(.38)	(.80)	(.04)	(.03)
50*	7.0	1.6	7.5	1.8	.47	.55
	(.32)	(.12)	(.27)	(.16)	(.01)	(.02)

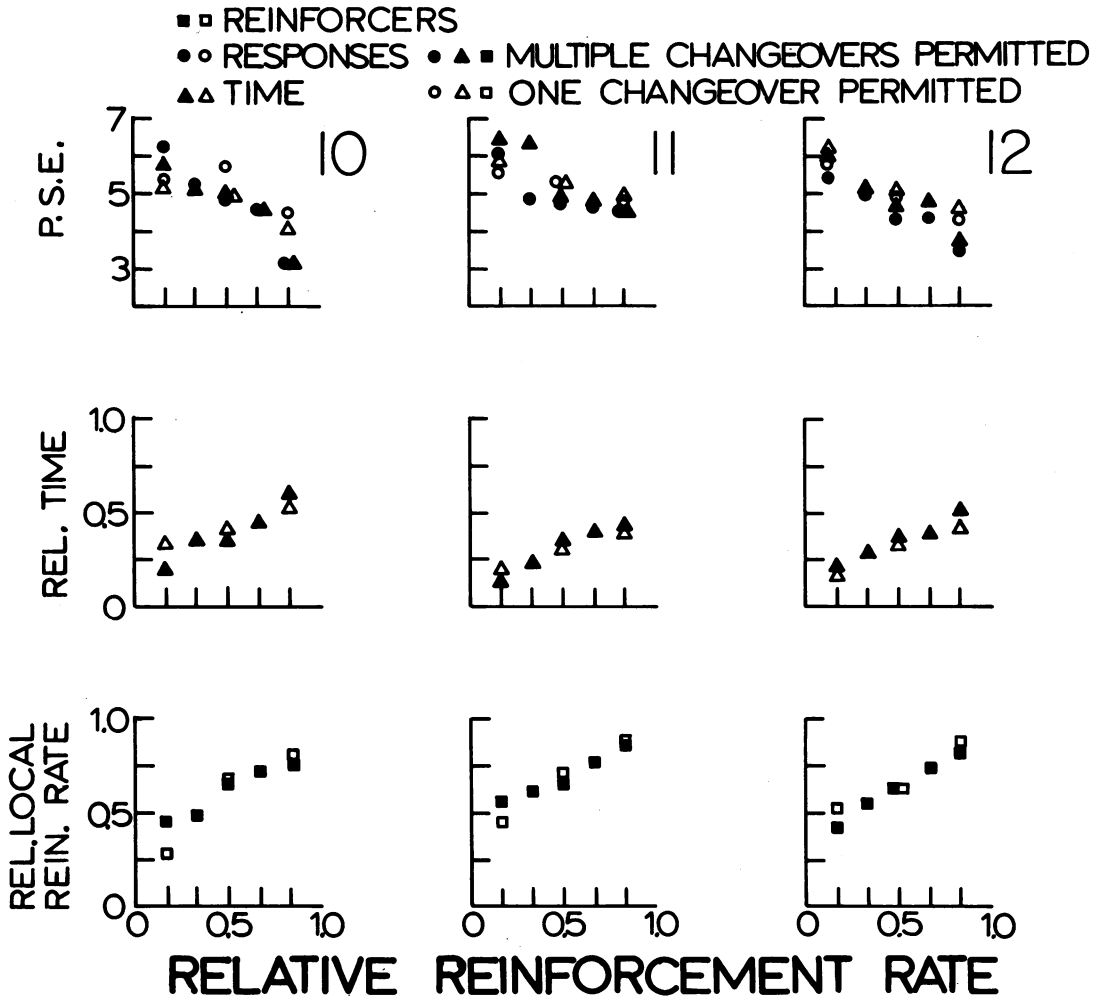* Reinforcers were scheduled during only half of the time periods (see text for details).

Fig. 8. Changes in three behavioral measures as a function of changing relative reinforcement rate (computed with respect to green-key produced reinforcers). The top portion shows the Point of Subjective Equality (PSE) or point at which green-key probability equaled .50 expressed in terms of time classes rather than seconds. The middle portion shows the relative time spent in the presence of green. The bottom portion shows the relative local reinforcement rate. Open or filled symbols represent conditions where one or multiple changeover responses were permitted in a time period. Data are means of the last five sessions.

overall relative reinforcement rate was the same in the presence of green and orange, local reinforcement rates were not equal. The bottom portions show relative local reinforcement rate (Rachlin, 1973). The measure is,

$$\frac{\dfrac{r_g}{T_g}}{\dfrac{r_g}{T_g} + \dfrac{r_o}{T_o}}$$

where r_g and r_o are the reinforcers delivered for green-key and orange-key responses, and T_g and T_o are the times spent in the presence of the green and orange stimuli. The results show that relative local reinforcement rate increased as more reinforcers were delivered for green-key responses. Relative local reinforcement rates tended to be above .5 in most conditions, thereby indicating a higher local reinforcement rate in green.

Figure 9 shows point of subjective equality for responses (top) and time (bottom) as a function of relative local reinforcement rate. The points indicate a negative relation between PSE data and relative reinforcement
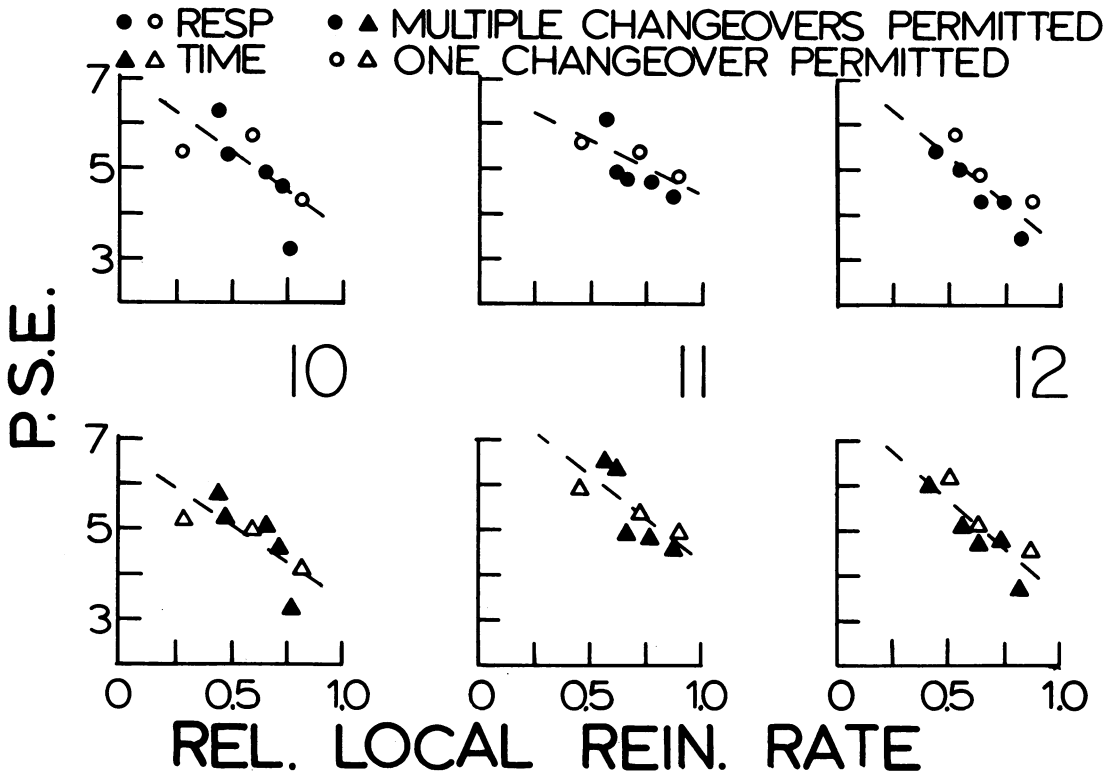
Fig. 9. Point of Subjective Equality (PSE) presented as a function of changes in the relative local reinforcement rate (computed with respect to green-key produced reinforcers). The top half shows PSE data for response probabilities. The PSE data are expressed in terms of the 10 time classes. Open or filled symbols represent conditions where one or multiple changeover responses were permitted.

rates. The pigeons tended to change from orange to green at an earlier time when the relative local reinforcement rate was increased for green-key responses. Best fitting straight lines (computed by the least-squares method) were drawn through the points; despite some variance, the lines provide a reasonable description of the data. The noteworthy feature of these lines is that they approximate the 5.5 point when the relative local reinforcement rate was .5 (with the one exception for Pigeon 11). The data imply that the pigeons would change from orange to green in accord with the time-class reinforcement consequences providing the local reinforcement rates were equal. Performance was biased when local reinforcement rates were not equal even though the overall relative reinforcement rates were equal.

When food was available on only half of the time periods, the relative amount of time and relative local reinforcement rates approxi-

mated .5 for both pigeons (see Table 2), and the PSE occurred between the fifth and sixth time classes. Probability functions (not shown) were quite similar to those already presented as were the changeover data.

DISCUSSION

Relative reinforcement rate was manipulated in Experiment 2. Choice performance shifted as relative reinforcement rate was varied. The ogival functions shifted from earlier to later time classes as relative reinforcement rates were varied, but the functions had similar slopes across conditions. These results suggest that changes in relative reinforcement rate affected response bias but not sensitivity, and they are consistent with previous results on duration discrimination using a trials procedure (Stubbs, 1976a).

Experiment 2 clarified the seemingly odd finding of Experiment 1 that the animals tended to shift to green before the contingen-

cies changed. The biased performance in these experiments appeared to result from different local reinforcement rates in the presence of orange and green. When the local reinforcement rate was higher in green than orange, the animals changed to green before the contingencies shifted. When, however, local reinforcement rates were equal in orange and green, the animals changed from orange to green between the fifth and sixth time classes, the time when the contingencies shifted.

The results may prove important for research on concurrent schedules. A basic finding of concurrent schedules research is the matching relation between behavioral measures and reinforcers (Catania, 1966; deVilliers, 1977; Herrnstein, 1970). If, for example, 75% of the reinforcers are scheduled for one response, 75% of the responses are emitted on that schedule and 75% of the animal's time is spent on that schedule. According to this view, overall relative reinforcement rate is seen as the factor controlling choice. There is, however, an alternate view, one that lays stress on the local rate of reinforcement (Rachlin, 1973). When, for example, an animal obtains 75% of its reinforcers on one schedule, 75 reinforcers might be delivered on one schedule and 25 reinforcers on the alternate schedule. If the animal matches, it might spend 75 min on the one schedule, obtaining 75 reinforcers, and 25 min on the other, obtaining 25 reinforcers. The result is that the animal receives one reinforcer per min in both schedules (75 reinforcers/75 min; 25 reinforcers/25 min), and local reinforcement rate is equal for the two schedules. When a subject matches time to reinforcers, the relative local reinforcement rates are equal (Rachlin, 1973). So the following questions arise. Is behavior primarily a function of the overall relative reinforcement rate with a resulting preference for a schedule due to a greater relative rate of reinforcement? Or is the local reinforcement rate the more important factor with the seeming preference a byproduct of the animals' equalizing the local reinforcement rate?

It is difficult to decide between the two views; the data of standard concurrent schedules are consistent with either view. However, Experiment 2 suggested that local reinforcement rate was the more important. It may be difficult to make conclusions about concurrent schedules since the present experiment involved a discrimination situation. With the procedural differences, the present findings do not provide a definitive answer, but they do suggest that local reinforcement rate might be the more important factor controlling choice.

EXPERIMENT 3

Experiment 2 demonstrated that changes in the relative local reinforcement rate influenced choice behavior. Experiment 3 was designed to go one step further by examining the effects of the local temporal distribution of reinforcers. In the previous experiments, reinforcers for orange-key responses were equally distributed between the five short short time classes and those for green-key responses between the five long. In contrast, the reinforcers for green-key responses were unequally distributed in Experiment 3. This arrangement kept the number of green-key reinforcers constant across conditions, but allowed for the majority of reinforcers to be delivered in a particular time class.

METHOD

Subjects

Pigeons 11 and 12 served.

Apparatus

The apparatus was the same as in Experiments 1 and 2.

Procedure

The procedure was similar to that of the previous experiments: with 0-to-15-sec time periods, orange-key responses produced food during the first five time classes (0 to 7.5 sec) and green-key responses produced food during the remaining five (7.5 to 15 sec), only one changeover response was permitted each time period, and a correction procedure was used.

Half of the reinforcers were delivered during the first five time classes and half during the last five. Reinforcers produced by orange-key responses were equally distributed in each of the first five time classes. In contrast, reinforcers produced by green-key responses were not equally distributed: 73% of these reinforcers occurred during one time class, and the remaining 27% was equally distributed among the four remaining time classes. The highest reinforcement frequency was scheduled in Time Class 10 in the first con-
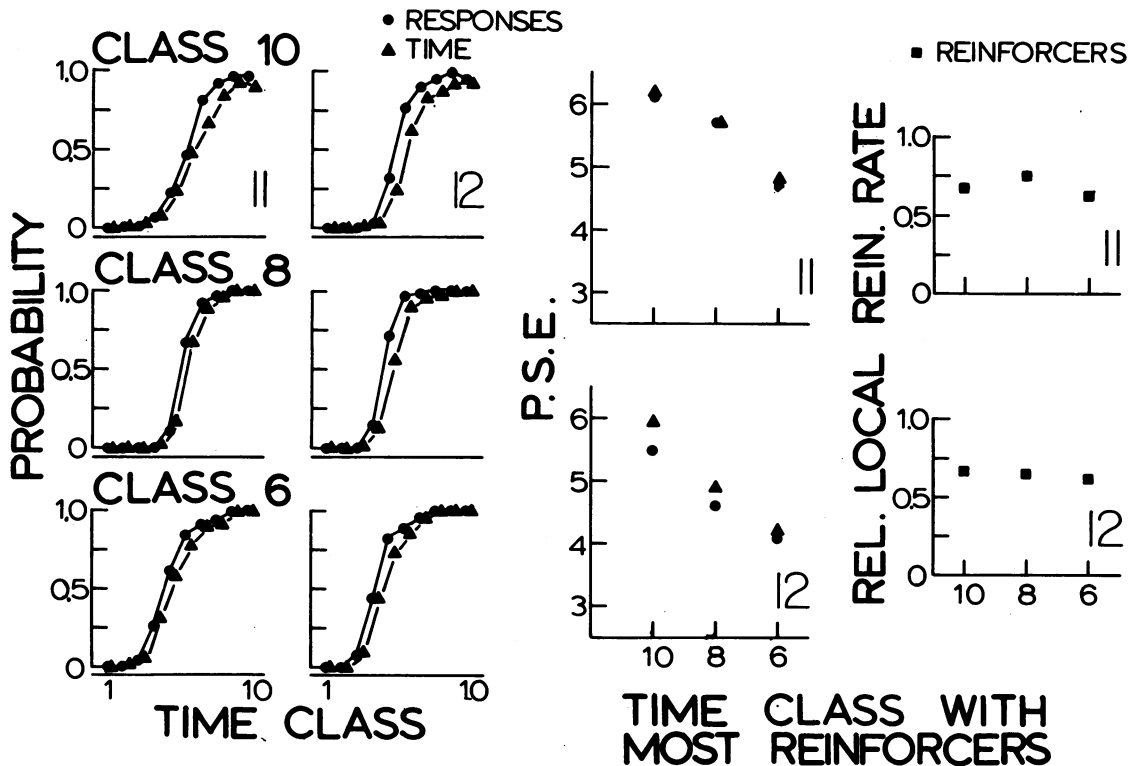
Fig. 10. The effects on different measures of changing the time class in which most green-key reinforcers were delivered. The left half shows probability measures; the right half shows summary measures. The data are means of the last five sessions.

dition, Time Class 8 in a second, and Time Class 6 in a third. The first and third conditions were in effect 24 sessions, the second for 25 sessions.

RESULTS

The left portions of Figure 10 show probability data both for responses and time. Ogival functions were obtained similar to those in the prior experiments. The ogival functions shifted to the left as the time class with the highest reinforcement frequency was changed from Class 10 to Class 6. Even though the number of reinforcers for green-key responses was the same, the pigeons shifted from orange to green earlier in time when the majority of reinforcers were delivered at earlier time classes. The middle section of Figure 10 shows that PSEs were located at earlier times when the highest food frequency was changed from Class 10 to Class 6.

Choice behavior shifted across conditions even when overall relative reinforcement rate was held constant. Choice behavior did not appear to change as a functions of changes in relative local reinforcement rate. The right-hand section of Figure 10 shows relative local reinforcement rates and indicates that this measure was more or less constant across conditions. So, behavior changed even when the local reinforcement rate in green remained roughly constant. Choice behavior was a function of the differential temporal placement of food in Time Classes 6 through 10.

DISCUSSION

Experiment 2 demonstrated that choice behavior was affected by the relative local reinforcement rate. Experiment 3 went one step further by demonstrating that choice was influenced by the temporal distribution of green-key reinforcers. Even when overall and local reinforcement rate remained roughly constant, behavior changed as a function of the temporal distribution of reinforcers. The findings parallel those of schedule research; for example, variable-interval schedules generate roughly constant response rates, but re-

sponse rates vary locally depending on the distribution of reinforcers (e.g., Catania and Reynolds, 1968). The results also support Gibbon's (1977) scalar expectancy theory. Gibbon has emphasized the distribution of reinforcers as a factor controlling choice. The present data agree by showing that the distribution of reinforcers, not just the number, affected performance.

GENERAL DISCUSSION

The present experiments used a free-operant procedure and obtained results that agree with those of the more commonly used trials procedures. There were new findings, of course, such as changes in discrimination with longer times and changes in choice due to local patterns of reinforcement. But the major finding is that the experiments in many ways support and agree with the earlier results.

Agreement between the two sets of data might be taken to imply that there is little reason to choose one procedure over the other or that there was little advantage adding a new procedure. However, each of the two procedures has its own advantages. One advantage of the free-operant procedures is that the data are more orderly and may be obtained in a shorter time than those of the trials procedure. The present data from a single session were much more regular than those combined over several sessions under the trials procedure. The orderly aspect of the data could prove useful for some research areas such as psychopharmacology. A second advantage is that the present procedure has closer ties to schedules research than does a trials procedure. It may prove easier to draw inferences about possible temporal discriminations that occur under schedules (Stubbs, 1976b). A disadvantage is that the free-operant results may be more subject to contaminating influences than the trials procedure. Numerous authors have pointed out that schedule performance is characterized by sequential dependencies, double pecks, autoshaped responses, and the like (e.g., Jenkins, 1970); these factors could interfere with inferences about choice responses as showing a temporal discrimination.

The trials procedure and the free-operant procedure each has its advantages and disadvantages. A researcher may for a particular purpose choose one or the other, but the two should also prove useful in combination. Similar results obtained by the two procedures allow for more definite statements about animals' temporal discrimination. The similarity of findings with the free-operant procedure to those of the trials procedure give added weight to the previous results; and the existing results with trials procedures strengthen the present findings. The similar results indicate that the findings are not limited to one specific procedure.

REFERENCES

Catania, A. C. Concurrent operants. In W. K. Honig (Ed.), *Operant behavior: Areas of research and application.* New York: Appleton-Century-Crofts, 1966.

Catania, A. C. Reinforcement schedules and psychophysical judgments: A study of some temporal properties of behavior. In W. N. Schoenfeld (Ed.), *The theory of reinforcement schedules.* New York: Appleton-Century-Crofts, 1970.

Catania, A. C., & Reynolds, G. S. A quantitative analysis of the responding maintained by interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior,* 1968, 11, 327-383.

Church, R. M., Getty, D. J., & Lerner, N. D. Duration discrimination by rats. *Journal of Experimental Psychology: Animal Behavior Processes,* 1976, 2, 303-312.

DeCasper, A. J., & Zeiler, M. D. Time limits for completing fixed ratios. IV. Components of the ratio. *Journal of the Experimental Analysis of Behavior,* 1977, 27, 235-244.

deVilliers, P. Choice in concurrent schedules and a quantitative formulation of the law of effect. In W. K. Honig and J. E. R. Staddon (Eds.), *Handbook of operant behavior.* Englewood Cliffs, N.J.: Prentice-Hall, 1977.

Eisler, H. Experiments on subjective duration 1868-1975: A collection of power function exponents. *Psychological Bulletin,* 1976, 83, 1154-1171.

Guilford, J. P. *Psychometric methods* (2nd ed.). New York: McGraw-Hill, 1954.

Gibbon, J. Scalar expectancy theory and Weber's Law in animal timing. *Psychological Review,* 1977, 84, 279-325.

Herrnstein, R. J. On the law of effect. *Journal of the Experimental Analysis of Behavior,* 1970, 13, 243-266.

Jenkins, H. M. Sequential organization in schedules of reinforcement. In W. N. Schoenfeld (Ed.), *The theory of reinforcement schedules.* New York: Appleton-Century-Crofts, 1970.

Platt, J. R. Temporal differentiation and the psychophysics of time. In M. D. Zeiler & P. Harzem (Eds.), *Advances in analysis of behaviour, Vol. 1: Reinforcement and the organization of behaviour.* Chichester, England: Wiley, 1979.

Rachlin, H. Contrast and matching. *Psychological Review,* 1973, 80, 217-234.

Rilling, M. Number of responses as a stimulus in fixed interval and fixed ratio schedules. *Journal of Comparative and Physiological Psychology*, 1967, **63**, 60-65.

Snapper, A. G., Ramsay, D. A., & Schoenfeld, W. N. Disruption of a temporal discrimination under response-independent shock. *Journal of the Experimental Analysis of Behavior*, 1969, **12**, 423-430.

Stubbs, A. The discrimination of stimulus duration by pigeons. *Journal of the Experimental Analysis of Behavior*, 1968, **11**, 223-258.

Stubbs, D. A. Response bias and the discrimination of stimulus duration. *Journal of the Experimental Analysis of Behavior*, 1976, **25**, 243-250. (a)

Stubbs, D. A. Scaling of stimulus duration by pigeons.

Journal of the Experimental Analysis of Behavior, 1976, **26**, 15-25. (b)

Stubbs, D. A. Temporal discrimination and psychophysics. In M. D. Zeiler & P. Harzem (Eds.), *Advances in analysis of behaviour, Vol. 1: Reinforcement and the organization of behaviour*. Chicester, England: Wiley, 1979.

Stubbs, D. A., Pliskoff, S. S., & Reid, H. M. Concurrent schedules: A quantitative relation between changeover behavior and its consequences. *Journal of the Experimental Analysis of Behavior*, 1977, **27**, 85-96.