

*SIGNAL DETECTION AND MATCHING:  
ANALYZING CHOICE ON CONCURRENT  
VARIABLE-INTERVAL SCHEDULES*

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Pigeons' pecks on a red key and a green key were followed by access to grain according to pairs of concurrent independent variable-interval schedules in a combined signal detection/matching law paradigm. Pecks on the red key were reinforced by the richer variable-interval schedule if a short-duration tone had been presented; pecks on the green key were reinforced by the richer variable-interval schedule if a long-duration tone had been presented. Pecks on the green key given a short-duration tone, or on the red key given a long-duration tone, were reinforced by the leaner variable-interval schedule. The data were analyzed according to both signal detection's and the matching law's separate measures of, first, the discrimination of the choices and, second, the bias to make one response or another. Increasing the difficulty of the tone-duration discrimination decreased both methods' measures of the discrimination of the choices and did not change both methods' measures of the bias to make one response or another. Changing the leaner variable-interval schedule so that it approached the richer variable-interval schedule decreased signal detection's measure of discrimination but left its measure of response bias and the matching law measures unchanged. Data collected only until a subject's first changeover response following presentation of a long or a short tone showed higher values for both methods' measures of discrimination, no change in signal detection's measure of response bias, and lower values for the matching law's measure of response bias. Relationships between the matching law's and signal detection's methods of analyzing choice are discussed. It is concluded that a signal detection analysis is more efficient for examining changes in the difficulty of a discrimination, whereas a matching law analysis is more effective for examining the effects of changes in relative reinforcer frequency.

*Key words:* signal detection, matching law, choice, temporal discrimination, response bias, key peck, pigeons

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The matching law (Herrnstein, 1961, 1970) and signal-detection theory (Green & Swets, 1966) both provide quantitative methods for analyzing choice. A direct comparison of the similarities and differences between these two methods would indicate how each may best be used and might also improve our understanding of both methods and of choice in general. The paradigms within which the matching law and signal detection theory are investigated differ somewhat, however. Therefore to facilitate comparisons between these two ways of analyzing choice, it will be helpful to first briefly outline the procedures as well as the assumptions of each.

### BACKGROUND

#### *Signal Detection*

The usual signal-detection procedure employs discrete trials. One of two explicit stimuli (signal plus noise or noise alone) is presented

at the start of each trial. The subject's task is to make one of two responses indicating whether the signal plus noise or noise alone was presented. A payoff, punishment, or feedback is ordinarily then presented, the trial ends, and after an intertrial interval a new trial begins. This procedure results in four possible types of response (see Figure 1). Sub-

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		STIMULUS	
		SIGNAL	NOISE
RESPONSE	SIGNAL	HIT (correct detection)	FALSE ALARM (error)
	NOISE	MISS (error)	CORRECT REJECTION

Fig. 1. Classification of responses in a signal-detection experiment.

stituting payoffs for each of the four classes of response in Figure 1 yields a payoff matrix.

The purpose of signal-detection theory has been to provide independent measures of the effects on responding of outcomes, and of the discrimination of the explicit stimuli. According to traditional signal-detection theory, "bias" will ideally be affected only by motivational factors (e.g., the values of the payoff matrix), whereas "sensitivity" will ideally be affected only by manipulations of the physical character of the signal and of the noise (Green & Swets, 1966; Swets, Tanner, & Birdsall, 1961). When the values of the payoff matrix have been varied, bias, not sensitivity, has indeed usually been affected (Davenport, 1968, 1969; Hobson, 1978; Hume & Irwin, 1974; Nevin, 1967; Stubbs, 1968, 1976a; Wright, 1972, Wright & Nevin, 1974), whereas varying the physical difference between the signal and the noise affects sensitivity (Clopton, 1972; Hume & Irwin, 1974; Rilling & McDiarmid, 1965; Terman & Terman, 1972; Wright, 1972). However, contrary to traditional signal-detection theory, reinforcing errors (i.e., reinforcement for false alarms and misses, which are no longer strictly errors as these responses do result in some reinforcement) affects sensitivity, not just bias (Nevin, 1970; Nevin, Olson, Mandell, & Yarensky, 1975; Nevin, Jenkins, Whittaker, & Yarensky, Note 1). Recent quantitative investigations of signal detection have tried to construct models of detection that can account for such findings (Davison & McCarthy, 1980; Nevin, Jenkins, Whittaker, & Yarensky, 1982).

#### The Matching Law

Experiments on reinforcer choice within a matching-law paradigm typically use continuous rather than trial procedures. Generally,

two variable-interval (VI) schedules program reinforcement for responses on two levers or two keys. In these experiments subjects must discriminate both the variations in reinforcer rates programmed by different VI schedules and also the source of the reinforcers delivered by the individual VI schedules (e.g., whether left or right lever presses are reinforced by a given VI schedule). The distribution of responses across the two alternatives reflects both of these types of discrimination. When subjects distribute their responses in proportion to the distribution of reinforcers, they are said to match (de Villiers, 1977).

In matching-law experiments response distribution is often affected by factors other than the actual reinforcer distribution. The terms "response bias" and "discriminability" can be used to classify these factors (see Baum, 1974). Response bias would occur if, for instance, one lever were harder to push than another due either to differences in the levers or to a physical asymmetry in the animal. Discriminability includes factors that affect the perceived differences between the two schedules of reinforcement, making these differences seem smaller or larger. For example, if a rat is being reinforced from a single food source for responses on two adjacent, identical levers, the differential consequences for responding on the two levers might not seem so marked.

Response bias and discriminability within the matching law are expressed as follows:

$$\frac{B_1}{B_2} = k \left( \frac{R_1}{R_2} \right)^a, \quad (1)$$

where  $B_1$  and  $B_2$  represent responses on two alternatives;  $R_1$  and  $R_2$ , reinforcers obtained by responses on the two alternatives;  $k$ , response bias; and  $a$ , discriminability (Baum, 1974). When  $a$  and  $k$  are equal to one there is ideal matching (matching directly to the rate of reinforcement). If  $k$  is greater than one, there is response bias for the first alternative; if  $k$  is less than one, there is response bias for the second alternative. If  $a$  is less than one, there is undermatching (low discriminability); if greater than one, overmatching (high discriminability). Note that the matching law's measure of discriminability,  $a$ , is affected by variations in both types of discrimination described above: reinforcer rate and reinforcer source. However, in the matching-law paradigm, presentations of the stimuli, the VI

schedules, are not as explicit as the presentation of the stimuli in the signal-detection paradigm.

### *Signal Detection and the Matching Law Compared*

The matching-law and signal-detection paradigms have much in common. Aside from certain basic procedural similarities such as the collection of steady-state data from a small number of subjects (see Nevin, 1969b, for a summary), both paradigms record response distributions following variations in stimuli and outcomes. Both attempt, sometimes without success (e.g., Nevin, 1970; Staddon, 1978), to separately measure the influence of these two factors, with the matching law using discriminability and response bias, and signal detection using sensitivity and bias, respectively. However, since in the matching-law paradigm no explicit stimuli are presented, Figure 1 is collapsed so that there is only one column and only two types of response: signal and noise (left and right) responses. Both of these types of response are used in calculating  $a$  and  $k$ ; therefore the matching law's measures of discriminability and response bias are not independent (see Staddon, 1978). The value of  $a$  measures the rate of change in the tendency to make one response or another as the VI schedules are changed. The value of  $k$  measures whatever constant tendency there is to make one or the other response. In the signal-detection paradigm, which uses the four types of responses diagrammed in Figure 1, sensitivity is measured by comparing hits with false alarms, and bias is measured by comparing hits and false alarms with misses and correct rejections (see Figure 1). Although signal detection's and the matching law's actual measures of the effects of varying stimuli and outcomes are not the same, the two theories are closely related.

### RATIONALE

Two approaches have been taken towards clarifying the relationship between signal-detection theory and the matching law. One approach has involved the construction of mathematical models incorporating elements of both paradigms (e.g., Davison & McCarthy, 1980; McCarthy & Davison, 1981; Nevin et al., 1982). These models have been fairly successful

at developing quantitative accounts of choice under varying stimulus and outcome conditions. Another approach has involved making comparisons of the matching-law and signal-detection methods of analysis by analyzing experimental data according to both methods (see, e.g., Elsmore, 1972; Killeen, 1978; Stubbs, 1976a). Yet all of these experiments allowed only one response per trial and none of them scheduled reinforcers according to variable-interval schedules, standard matching-law procedure. Therefore any matching-law analysis of the results from these experiments has limitations.

It may be possible, however, to design a procedure similar enough to both the standard matching-law and signal-detection paradigms so that the data could reasonably be analyzed according to the standard methods of each paradigm. Signal-detection theory does not require that there be only one response per trial, as long as the discrimination involved prior to responding is clear (Green & Swets, 1966, p. 11). This suggests the possibility of using a signal-detection trials procedure with an explicit discrimination but with more than one response permitted per trial and with reinforcers programmed according to VI schedules, similar to a matching-law experiment. There have been previous signal-detection experiments in which the prior explicit discrimination was between a pair of schedules (e.g., Lattal, 1979; Mandell, 1981; Rilling & McDiarmid, 1965), and previous matching-law experiments in which discrete trials were used (e.g., Nevin, 1969a; Shimp, 1966).

Consider, then, an experiment in which the subjects are first required to discriminate between explicit stimuli; one VI schedule programs reinforcers for correct responses (hits and correct rejections), while another, leaner, VI schedule programs reinforcers for "errors" (false alarms and misses); and the VI schedule for errors and the difficulty of the explicit discrimination are varied. In a matching-law analysis the two types of responses measured would be correct and incorrect responses, instead of the usual left and right responses. Since subjects must first discriminate the explicit stimuli that are presented, in addition to the reinforcement schedules and the sources of the reinforcers, the extent of a subject's discrimination between the explicit stimuli would determine a limit for  $a$ . As the explicit

discrimination was made more difficult, discriminability ( $a$ ) of the differential reinforcement provided by the VI schedules for correct and incorrect responses should therefore decrease (Baum, 1974; Bourland & Miller, 1981; Miller, Saunders, & Bourland, 1980). Variations in the VI schedules for correct and incorrect responses should affect the distribution of correct and incorrect responses but not discriminability of reinforcement or response bias.

A signal-detection analysis also predicts that increasing the difficulty of the explicit discrimination should decrease sensitivity, but changing the reinforcer distribution should produce changes in response distribution. In addition, to the extent that errors are reinforced, previous research predicts, contrary to traditional signal-detection theory, that sensitivity should decrease.

Thus, the present experiment has several objectives. First, it will examine matching in an experiment in which subjects must make an explicit discrimination between presented stimuli before discriminating reinforcer rate and the source of reinforcement. Second, the experiment will examine signal detection in a situation in which responding is measured in a free-operant setting. For both the matching-law and signal-detection analyses the effects of varying the difficulty of the explicit discrimination and of varying relative reinforcer rate will be of specific concern. Not only should the experiment provide information about matching and signal detection in more general contexts, but it should also permit a better understanding of the relationship between signal detection and the matching law.

## METHOD

### *Subjects*

Four adult White Carneaux pigeons, numbered 1, 2, 3, and 4, served in this experiment. They were maintained at 80% of their free-feeding weights. All pigeons had previously participated in a variety of operant conditioning experiments, but none of these experiments had employed a signal-detection paradigm.

### *Apparatus*

The experimental chamber, one side of a partitioned ice chest, was 37.5 cm long, 30 cm

wide, and 30 cm high. Two response keys were mounted in the partition wall of the chamber. The keys were 12 cm apart, and each required a minimum force of .12 N to operate. Each key could be transilluminated by two 6-W green lights and two 6-W red lights. A food hopper below the keys provided access to mixed grain. Two 6-W white lights were located above a Plexiglas panel in the ceiling of the chamber. A Sonalert was situated just above the hopper mechanism behind the partition and outside of the chamber. A speaker, also located behind the partition, produced continuous white noise that helped mask extraneous sounds. An air blower provided ventilation. A PDP-8 computer in another room controlled the stimuli and recorded responses using a SKED program.

### *Procedure*

Noncorrection procedures were used. The pigeons first participated in five months of training during which they learned to peck a red key after presentation of a short tone and a green key after presentation of a long tone (for previous signal-detection experiments employing a duration discrimination task see Elmsmore, 1972; Kinchla, 1970; McCarthy & Davison, 1980b; Stubbs, 1968, 1976a, 1976b). At first only the "correct" key was illuminated after each tone presentation and each correct response was followed by reinforcement. Next both keys were lit, one red and one green, and finally reinforcement programming for pecks on the correct key was changed to a VI 5-sec schedule.

During the actual experiment each session began with illumination of the white overhead lights. These lights remained on throughout the session. Five seconds after the start of a session a trial began and the Sonalert emitted a tone. A probability generator set at .5 determined whether a short or a long tone was emitted. Immediately after the tone terminated, both keys were transilluminated, one key with red light and the other key with green light. They remained illuminated until a reinforcer was received. Key color was determined nonsystematically for each trial in order to prevent position biases. Pecks on either lit key were followed by a feedback click. Pecks on the red key following a short tone or the green key following a long tone, "correct" pecks, were reinforced with 2.5-sec access to food according to a VI schedule. Pecks on the red key

following a long tone or the green key following a short tone, "incorrect" pecks, were reinforced with 2.5-sec access to food according to a leaner VI schedule or were not reinforced at all. The VI schedules were constructed according to the distribution given by Fleshler and Hoffman (1962). VI schedules for correct and incorrect pecks were timed independently. The timers operated only while the key lights were on.

A 1-sec changeover delay (COD) was in effect; 1 sec had to elapse after a changeover response from a red to a green key or vice versa, or after the first response during a trial, before a subsequent key peck could deliver a reinforcer. The purpose of the COD was to decrease the probability of reinforcement of sequences of responses involving both keys. Such reinforcement can decrease choice discrimination as indicated by undermatching (de Villiers, 1977) and by a lower value of signal detection's measure of sensitivity.

A trial terminated with food delivery. After a 5-sec intertrial interval the Sonalert came on and another trial began. Sessions ended after 50 trials. Sessions were conducted 5 to 6 days per week.

The VI schedules, the tone durations, and the number of sessions each condition was in effect are shown in Table 1. Conditions were changed when all birds simultaneously satisfied a stability criterion. This criterion speci-

fied a minimum of 10 sessions in a condition. In addition, in at least the last five consecutive sessions, for each pigeon the percentage of correct responses had to be neither higher nor lower than the percentage of correct responses in all previous sessions within that condition.

The fourth pigeon made only 61% correct responses in the first condition. The first three subjects, however, made 73%, 68%, and 78% correct responses. With respect to time spent pecking, the fourth pigeon pecked approximately according to chance, responding correctly only 48% of the time, as compared with 65%, 62%, and 69% for the other three pigeons. Since the fourth pigeon did not appear to have acquired a good discrimination, it was dropped from the experiment.

## RESULTS

### Overall Performance

Data were analyzed using the results of the last five sessions from each condition, these being stable data as defined by the stability criterion. Time spent responding on a particular key during a trial was calculated as the cumulative time during a trial between a peck on that key and a peck on the other key or the receipt of a reinforcer. Data were recorded separately for the time until the first changeover response, or the time until the end of a trial if there were no changeover responses in a trial, and over the whole trial.

Total session time remained fairly constant throughout the experiment ( $M = 16.4$  min,  $SEM = .6$ ,  $N = 51$ , 17 conditions and 3 animals). The mean time during a trial until the first changeover, or until the end of a trial if there were no changeovers in a trial, was 5.3 sec ( $SEM = .2$ ,  $N = 51$ ). This compares with a total mean of 6.1 sec that the keylights were on during a trial ( $SEM = .2$ ,  $N = 51$ ). There were an average of 21.8 changeovers per session ( $SEM = 1.8$ ,  $N = 51$ ), or about .4 changeovers per trial.

Overall, the procedure was successful at engendering a discrimination between the red and green keys and the correct and incorrect keys. Neither the subjects' responses nor the computer's stimulus presentations showed a significant bias for the red (short tone) or green (long tone) keys. In addition there were no significant differences between the amount of time the keylights were on when a red- or a

Table 1  
Summary of Experimental Conditions

Condition Number	Short Tone (sec)	Long Tone (sec)	VI Schedule (sec)		Number of Sessions
			Correct Responses	Incorrect Responses	
1	2	10	5	extinction	22
2	2	10	5	120	40
3	2	10	5	60	37
4	2	10	5	30	26
5	2	10	5	15	22
6	2	10	5	7.5	14
7	2	10	5	5	15
8	2	10	5	7.5	18
9	2	10	5	15	19
10	2	10	5	30	16
11	2	10	5	60	17
12	3	9	5	60	29
13	3	9	5	30	29
14	3	9	5	15	26
15	3	9	5	30	35
16	3	9	5	60	17
17	3	9	5	120	17

green-key response was correct, between the number of red and green pecks until the first changeover or the end of the trial if there were no changeovers, and between red and green pecks over the whole trial.

Observations of the pigeons' behavior indicated that they had no difficulties discriminating the onset and the offset of the tone. The pigeons almost always faced the keys while the tone was on and began pecking as soon as the tone terminated and the keylights came on. The mean latency from keylight onset to the first response in a trial was 1.7 sec ( $SEM = .1$ ,  $N = 51$ ). Very few responses were made while the tones were on or during the intertrial intervals ( $M = .3$  responses per session,  $SEM = .3$ ,  $N = 51$ , while the tones were on;  $M = .01$  responses per session,  $SEM = .01$ ,  $N = 51$ , during the intertrial intervals). In addition the tone was easily audible to a human from all areas of the chamber.

The mean accuracy levels in this experiment were 70% correct responses ( $SD = 6$ ,  $N = 3$ ) and 66% correct time spent responding ( $SD = 8$ ,  $N = 3$ ) over the whole trial. These accuracy levels were high enough to indicate that there was discrimination between the two tones and yet low enough that ceiling effects were not a problem. The fact that accuracy levels were similar on the red and green keys adds support to the assumption that there was an adequate red-green discrimination (70% correct on red,  $SD = 8$ ; 71% correct on green,  $SD = 4$ ;  $t(2) = -.37$ ,  $p > .50$ ).

Figure 2 shows the percentage of red responses and the percentage of correct responses as a function of the VI schedule for incorrect responses during successive conditions in the experiment. Note that for each pigeon the first one or two points for percentage correct are lower than the following points, suggesting that during the first few conditions the pigeons were still learning the discrimination. For Pigeons 1 and 3, the percentage of red responses was fairly constant throughout the experiment, while the percentage of correct responses generally decreased as the reinforcement for errors was increased and as the tone-duration discrimination was made more difficult. For Pigeon 2 the same patterns may be present but are obscured in the 7.5-sec and 5-sec incorrect VI reinforcement conditions, when this pigeon seems to have lost the discrimination as evidenced by the overlap in the percentage of red

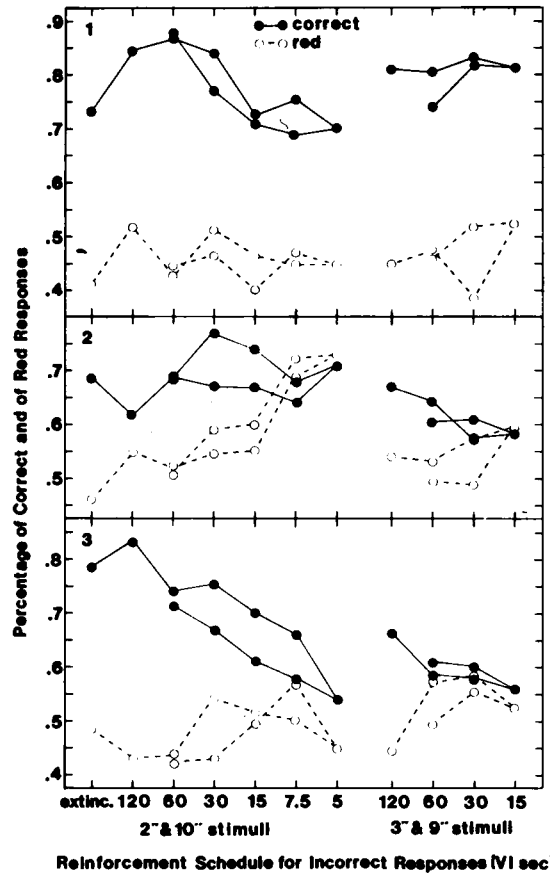


Fig. 2. The percentage of red-key responses and correct-key responses as a function of each condition. Data are shown for each of the three subjects. Points are connected according to the order in which conditions were conducted, starting with the left-most points.

and the percentage of correct responses. All pigeons, despite the fact that conditions were run to stability, show behavioral hysteresis (Stevens, 1957).

#### Signal Detection

Figure 3 shows the classification of responses for the signal-detection analysis in the present experiment (cf. Figure 1). To determine the values of sensitivity and bias according to signal-detection theory, the nonparametric methods of Grier (1971) were used (for other researchers who have used these methods see, for example, Lattal, 1979; Nevin et al., 1975; Stubbs, 1976a; Wright & Nevin, 1974). The computational formulas used for calculating Grier's (1971) nonparametric indices of sensitivity ( $A'$ ) and bias ( $B''$ ) were as follows:

		STIMULUS	
		SHORT TONE	LONG TONE
RESPONSE	RED PECK	HIT red / short	FALSE ALARM red / long
	GREEN PECK	MISS green / short	CORRECT REJECTION green / long

Fig. 3. Classification of responses for the signal-detection analysis in the present experiment.

$$A' = \frac{3 + b + \frac{a(b-1)}{(1-a)} - \frac{a}{b}}{4},$$

where  $a = p(\text{false alarm})$ , false alarms/(false alarms + correct rejections); and  $b = p(\text{hit})$ , hits/(hits + misses);

$$B'' = \left(\frac{y-x}{x}\right) 100, \quad \text{if } b > 1.0 - a,$$

and

$$B'' = \left(\frac{y-x}{y}\right) 100, \quad \text{if } b > 1.0 - a,$$

where  $x = a/b$ , and  $y = (1-b)/(1-a)$ , and  $a$  and  $b$  are as above. In the present experiment Grier's index of sensitivity,  $A'$ , represents subjects' sensitivity between the long and short tones. Grier's index of bias,  $B''$ , represents subjects' bias to make a response on the red (short-tone correct) or the green (long-tone correct) keys.

Figures 4 and 5 plot  $A'$  as a function of condition separately for each pigeon and averaged over all three pigeons. Data for both whole trials and only until the first changeover (or the end of a trial if there were no changeovers in a trial) are shown. Figure 4 uses the probability of a hit response and of a false alarm response to calculate  $A'$ . Figure 5 uses the probability of spending time responding on a hit key and of spending time responding on a false alarm key to calculate  $A'$ . Note the lower values of  $A'$  for data for the whole session as compared with data before the first changeover, and the general increase in  $A'$  for the first 2 to 3 conditions.

Figures 4 and 5 also appear to show that  $A'$  decreases as the VI schedule for incorrect responses approaches the 5-sec VI schedule for correct responses. If this is true, the initial

portions of the functions in Figures 4 and 5 should have a negative slope and the final portions of the functions should have a positive slope (i.e., both portions should show a negative slope as the VI schedule for incorrect responses approaches that for correct responses). To test this hypothesis statistically, straight lines were fit to the initial and final portions of the functions and then a  $t$  test was performed to determine if these negative and positive slopes were significantly different from zero (Snedecor & Cochran, 1967, p. 153). Specifically, one line was fit to the initial part of each function ignoring Conditions 1 to 3 if the values of  $A'$  in those conditions were increasing (indicating the discrimination was still being acquired), through Condition 5 in which reinforcement was equal for correct and incorrect responses (Condition 14 for the harder tone discrimination), or the next condition if that value of  $A'$  were lower than in the preceding condition indicating hysteresis, and so on. A second line was fit from the last point of the first line through the last point of the function. For the 32 functions depicted in Figures 4 and 5, of the 64 possible negative- and positive-slope lines, 30 were in the predicted direction and had slopes significantly different from zero (the test could not be performed for nine of the lines as they consisted of only two points). Thus  $A'$  does appear to decrease as the VI schedule for incorrect responses approaches that for correct responses.

To determine whether  $A'$  values changed when the difference between the tone durations was made smaller,  $A'$  values can be compared for conditions in which the current and preceding (to control for hysteresis effects) VI schedules are similar, with only the tone-duration discrimination involved differing, and for the VI 60-sec incorrect schedule conditions just prior to and just following the change in the duration stimuli. There are four such comparisons for each pigeon, Condition 4 with Condition 13, 5 with 14, 11 with 12, and 11 with 16. Each of these comparisons can be assessed using whole-trial as well as until-the-first-changeover data, and response-based and time-based data, 48 comparisons in all. Of these 48 comparisons, 42 show a smaller  $A'$  in the smaller tone-duration difference conditions. All of the exceptions occurred with the first pigeon. These findings can be seen most easily by looking at the averaged data.

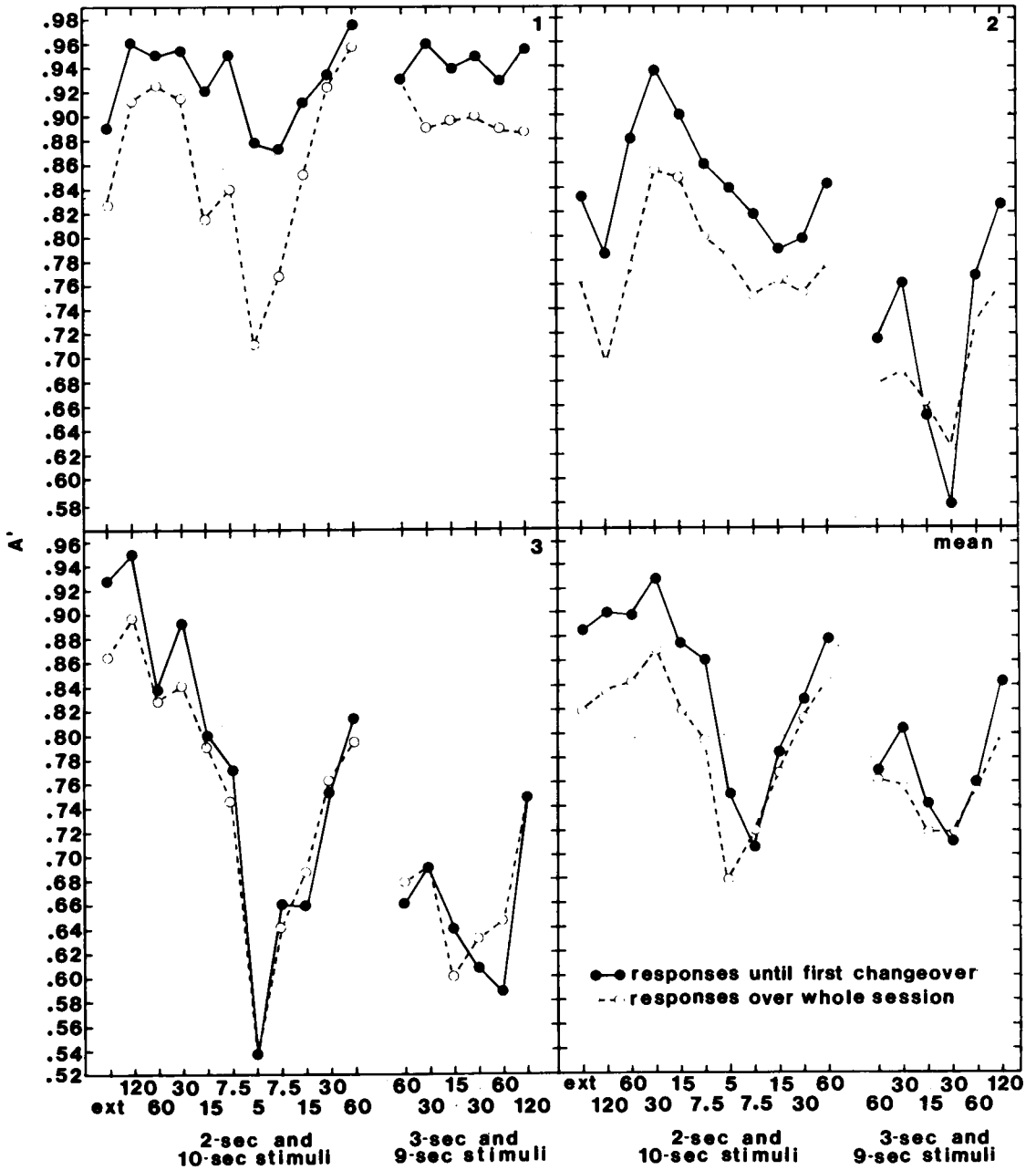


Fig. 4. Signal-detection sensitivity,  $A'$ , as a function of condition. Data are shown for each of the three subjects and for the mean of all three subjects.  $A'$  is based on the number of pecks the subjects made on each key.

Figures 6 and 7 plot Grier's index of bias,  $B''$ , as a function of condition separately for each pigeon and averaged over all three pigeons. Data for both the whole trial and for the time until the first changeover, or until the end of a trial if there were no changeovers in

that trial, are shown. Figure 6 plots response data and Figure 7 plots time spent responding data.

In these graphs  $B''$  does not decrease as the VI schedule for incorrect responses approaches the VI schedule for correct responses. When



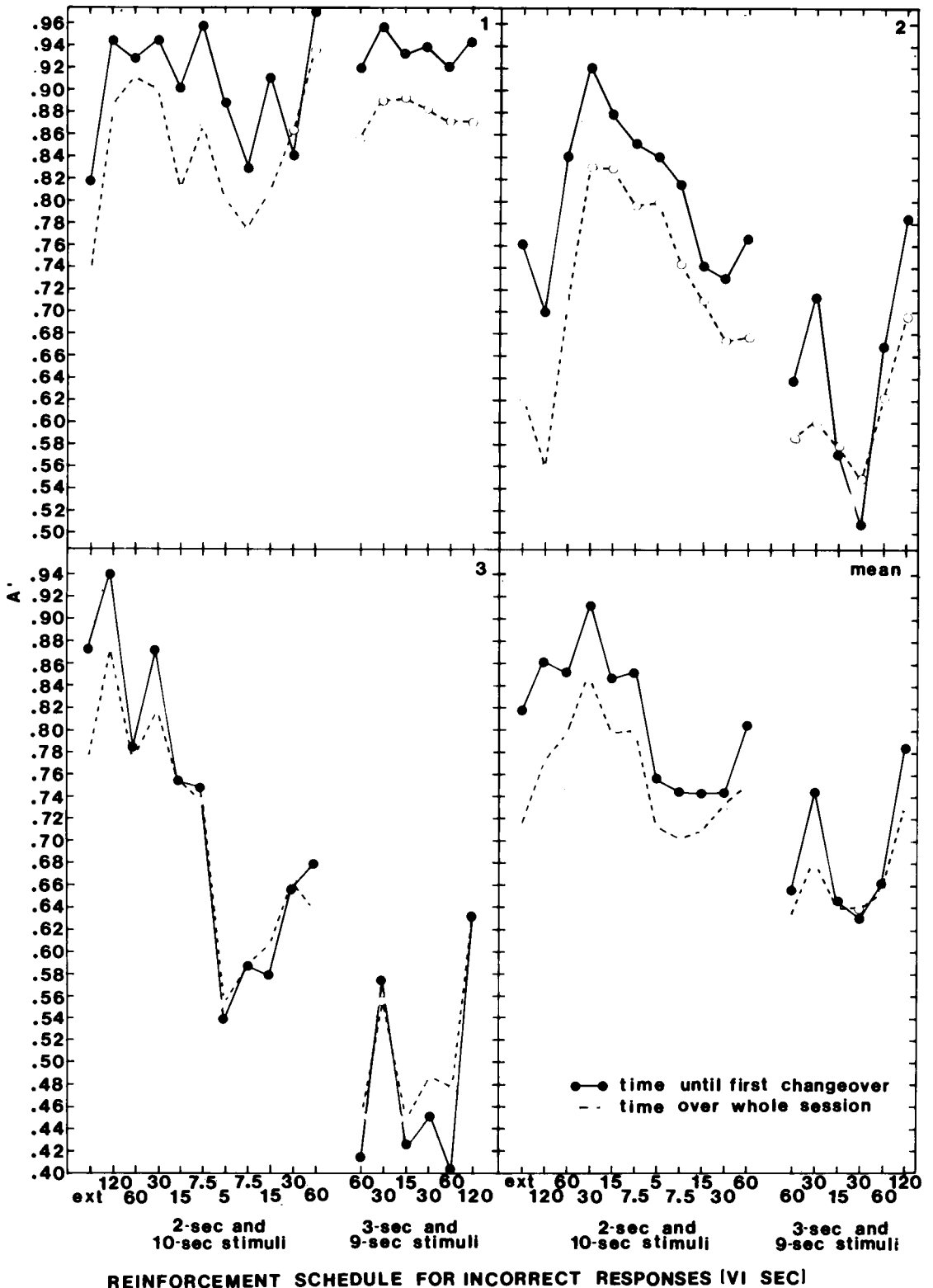


Fig. 5. Signal-detection sensitivity,  $A'$ , as a function of condition. Data are shown for each of the three subjects and for the mean of all three subjects.  $A'$  is based on the time the subjects spent pecking on each key.

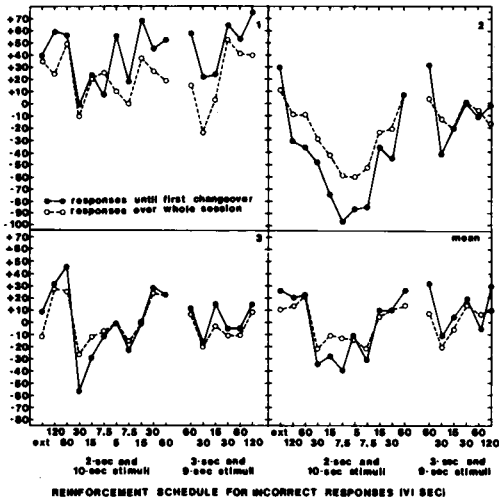


Fig. 6. Signal detection bias,  $B''$ , as a function of condition. Data are shown for each of the three subjects and for the mean of all three subjects.  $B''$  is based on the number of pecks the subjects made on each key.

lines were fit to the data in Figures 6 and 7 for  $B''$  as described above for  $A'$ , only 10 of the 64 possible lines showed significant negative slopes as the VI schedule for incorrect responses approached the 5-sec VI schedule for correct responses, and eight of these occurred in the data of Pigeon 2 with the easier tone discrimination. As will be recalled from Figure 2, Pigeon 2 appeared to have lost its discrimination in Conditions 6 to 8, responding a higher percentage on the red than the correct keys.

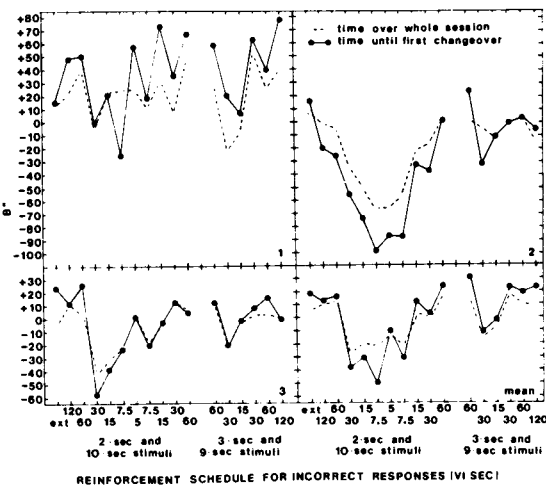


Fig. 7. Signal detection bias,  $B''$ , as a function of condition. Data are shown for each of the three subjects and for the mean of all three subjects.  $B''$  is based on the time the subjects spent pecking each key.

$B''$  also does not differ for the two pairs of tone durations. When the data were examined as described for  $A'$  above, in only 20 of 48 comparisons were the values of  $B''$  lower for the conditions in which the difference between the tone durations was smaller.

The data were also analyzed according to what McCarthy and Davison (1980a) call the point estimates of discrimination (i.e., sensitivity, hereafter called  $PED$ ) and bias (hereafter known as  $PEB$ ). The computational formulas for McCarthy and Davison's (1980a)  $PED$  and  $PEB$  are as follows:

$$PED = \frac{1}{2} \log \left( \frac{\text{Hits} \times \text{Correct Rejections}}{\text{False Alarms} \times \text{Misses}} \right)$$

and

$$PEB = \frac{1}{2} \log \left( \frac{\text{Hits} \times \text{False Alarms}}{\text{Correct Rejections} \times \text{Misses}} \right)$$

In addition, Davison and McCarthy's (1980) correction factor ( $CF$ ) for reinforcement for errors was used,

$$\frac{(R_{\text{Hits}} + R_{\text{Correct Rejections}}) - (R_{\text{False Alarms}} + R_{\text{Misses}})}{(R_{\text{Hits}} + R_{\text{Correct Rejections}}) + (R_{\text{False Alarms}} + R_{\text{Misses}})}$$

where  $R_i$  = reinforcers for responses of type  $i$ . Davison and McCarthy (1980) suggested that  $PED/CF = \log d$ , where  $\log d$  is also known as discriminability. The values of  $\log d$ , and thus  $PED/CF$ , are supposed to remain constant with reinforcement for errors, whereas  $PED$  alone should decrease with reinforcement for errors as dose  $A'$ . Figures 8 and 9 show examples of these analyses using data from Subject 1 with responses as the dependent variable. Reinforcers before the first changeover (i.e., on trials in which there were no changeovers) were not recorded separately in Condition 1. Therefore no data for  $PED/CF$  until the first changeover are shown for Condition 1 in the lower half of Figure 8. In general, the results from the analyses of  $PED$  and  $PEB$  were similar to those obtained with Grier's (1971) non-parametric methods. Dividing  $PED$  by  $CF$  does appear to remove the systematic decrease in  $PED$  with increasing reinforcement for errors, although the data show a lot of variability.

### Matching Law

The data were also analyzed according to Baum's (1974) generalized matching law so that response bias and under- or overmatching could be assessed. The logarithm of Equation

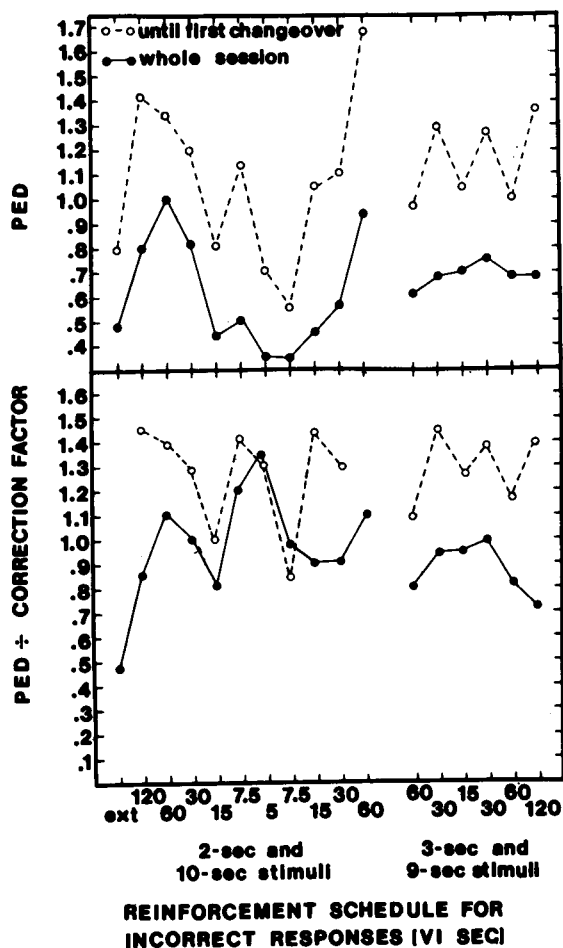


Fig. 8. Point estimates of discrimination ( $PE_D$ ), and  $PE_D$  divided by a correction factor ( $CF$ ) for reinforcement for errors, as a function of condition. Data are shown for Subject 1 and are based on the number of pecks the subject made on each key.

1,  $\log(B_1/B_2) = a \log(R_1/R_2) + \log k$ , is an equation for a straight line. Therefore data were fit to the matching law by plotting reinforcer and behavior ratios in log-log coordinates and determining the best fitting line by the method of least squares. Data from the first two conditions were not used to calculate the best fitting lines since Figure 2 and the signal-detection analyses suggested that the pigeons were still learning the discrimination during that time period (see Pastore & Scheirer, 1974, for further discussion of how training can affect signal-detection sensitivity).

Figures 10 and 11 show the two most common matching law dependent variables (de Villiers, 1977) applied to the present experiment, the ratios of correct VI divided by incorrect

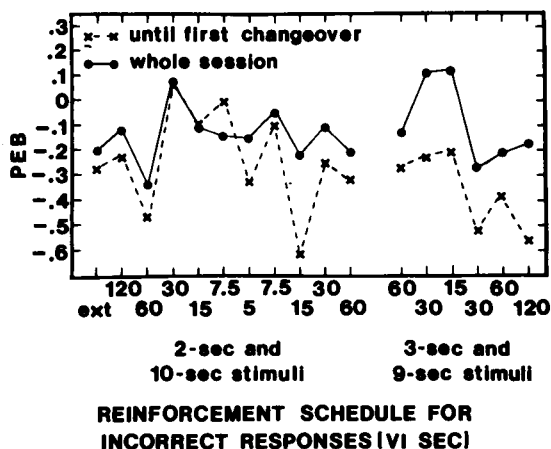


Fig. 9. Point estimates of bias ( $PE_B$ ) as a function of condition. Data are shown for Subject 1 and are based on the number of pecks the subject made on each key.

VI schedule responses or the same ratios using time spent responding, plotted as a function of ratios of correct divided by incorrect obtained reinforcers. Data are shown separately for all three pigeons, for the two pairs of tone durations, and for whole-trial and until the first changeover data. Data are not shown for the first condition in which there was no reinforcement for errors. The values of  $a$  and  $k$  (the slopes and intercepts) and the coefficient of variation from regression of the best fitting lines are given in each graph.

Note that, consistent with the previous analyses, in some cases the data from the second condition appear discrepant. Note also that, except for the second pigeon whose slopes were quite low to begin with, the slopes decrease for the conditions in which the difference between the tone durations was smaller. All of the slopes are less than 1.0, indicating undermatching; the pigeons were not as sensitive to changes in the VI schedules as ideal matching would predict. There is no clear pattern of change in the intercepts when the tone duration discrimination is changed. The intercepts are generally close to or greater than one, indicating a bias to respond on the key for which reinforcers were scheduled by the richer, correct VI schedule. This means that over all conditions the subjects tended to respond more on the richer VI than the ideal matching law would predict. In general the slopes and intercepts are closer to 1.0 for data obtained only until the first changeover, or until the end of

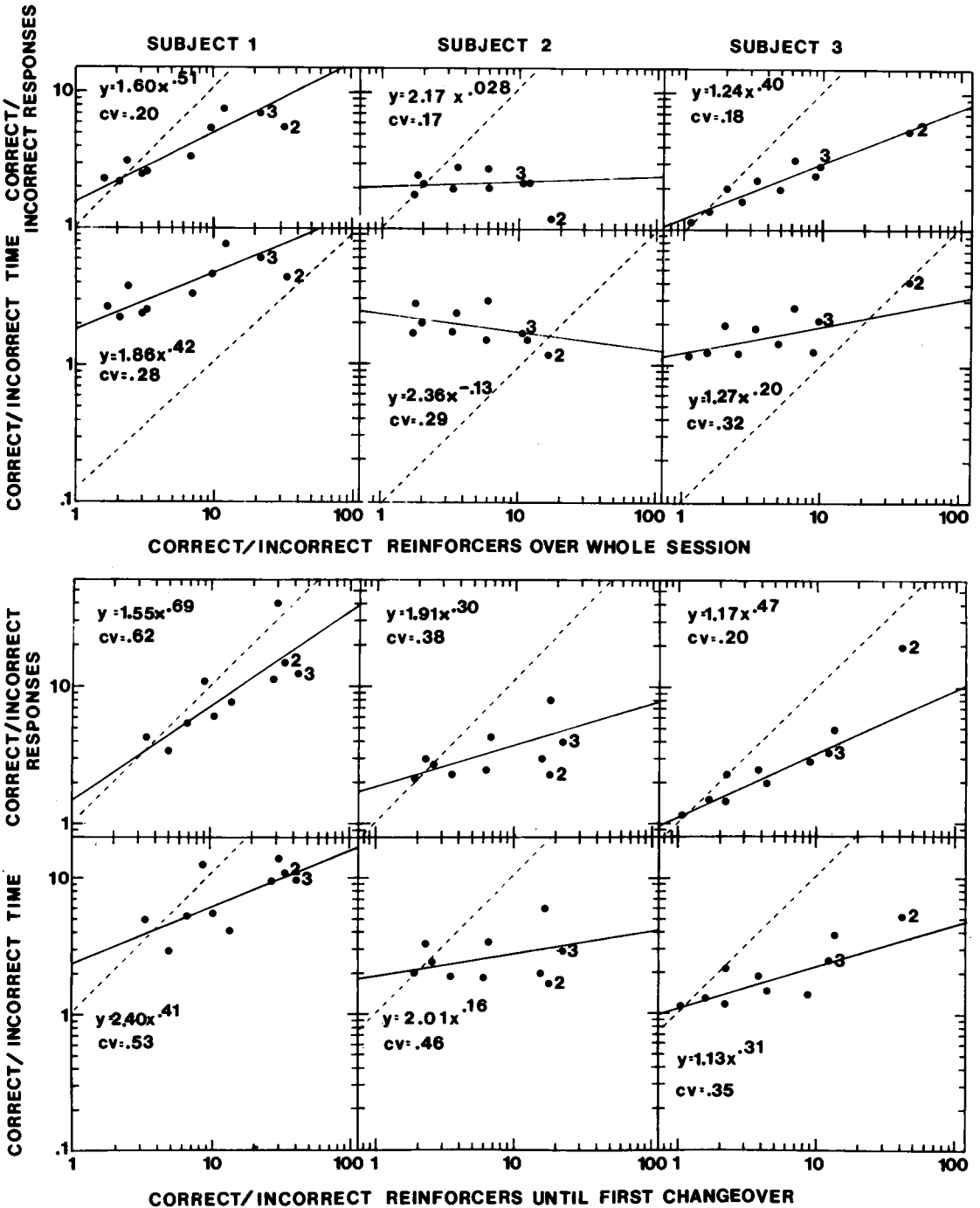


Fig. 10. Correct (richer VI schedule) divided by incorrect (leaner VI schedule) pecks or time spent pecking as a function of correct divided by incorrect reinforcers, in logarithmic coordinates, for the conditions using the 2-sec and 10-sec duration stimuli. The best fitting (solid) lines, calculated by the method of least squares, are shown in each graph along with the equation for these lines (in linear coordinates) and the coefficients of variation from regression. The dashed lines represent matching directly to reinforcement,  $y = 1.0(x)^{1.0}$ . The numbers 2 and 3 beside individual data points indicate the second and third condition data. Best fitting lines were calculated without using the data from the first two conditions.

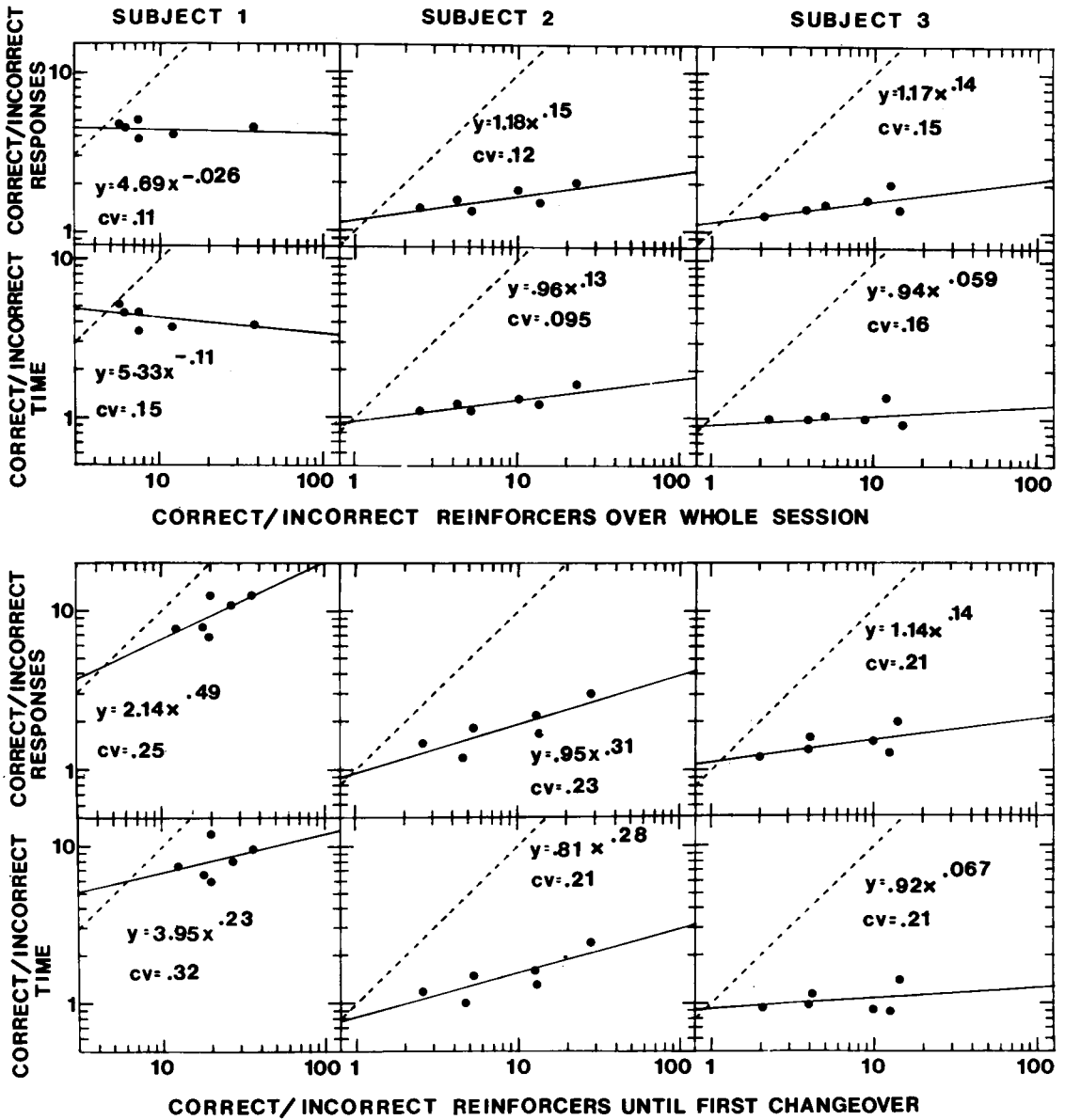


Fig. 11. Correct (richer VI schedule) divided by incorrect (leaner VI schedule) pecks or time spent pecking as a function of correct divided by incorrect reinforcers, in logarithmic coordinates, for the conditions using the 3-sec and 9-sec duration stimuli. The best fitting (solid) lines, calculated by the method of least squares, are shown in each graph along with the equation for these lines (in linear coordinates) and the coefficient of variation from regression. The dashed lines represent matching directly to reinforcement,  $y = 1.0(x)^{1.0}$ .

a trial if there were no changeovers in a trial.

Figures 10 and 11 are plotted using obtained rather than programmed reinforcer ratios, consistent with usual matching law data analysis procedure (de Villiers, 1977). Obtained reinforcer ratios in this experiment were not very different from programmed reinforcer ratios, however. The mean percentage difference between obtained and programmed reinforcer

ratios was 10.2% ( $SEM = 5.0$ ,  $N = 48$  for all conditions and animals excluding the first condition). In addition the mean number of responses per reinforcer, which, if close to 1.0, suggests determination of reinforcer distribution by response distribution (Herrnstein, 1970), was high (9.5 responses per reinforcer,  $SEM = .3$ ,  $N = 51$ ). However, the reinforcer ratio was not equal to 1.0 when the correct and

incorrect VI schedules were equal (each 5 sec). Instead, over whole trials it was 1.7, 1.8, and 1.1 for the three pigeons, respectively. The corresponding response ratios were 2.3, 2.5, and 1.2. These values demonstrate the effects of hysteresis. The subjects' response preferences, and consequently obtained reinforcer ratios, were clearly affected somewhat by the contingencies in prior conditions in which more reinforcers were scheduled for "correct" than "incorrect" responses (see Nevin et al., 1975, for similar findings).

### DISCUSSION

Manipulating the VI schedule for incorrect responses and manipulating the tone-duration discrimination had predictable results with respect to the matching-law and signal-detection analyses' measures of sensitivity and motivation. In particular, for the matching law, a comparison of the data obtained from the present experiment with data obtained from traditional matching-law experiments reveals the effects of the changes made in the present experiment from the standard matching-law procedure. First, all of the best fitting lines showed substantial undermatching (cf. Baum, 1979). This was undoubtedly due in part to the difficulty of the added tone-duration discrimination; undermatching increased when the discrimination was made more difficult (cf. Bourland & Miller, 1981; Miller et al., 1980). Since reinforcement differed for correct and incorrect responses and since correct and incorrect responses were defined by the tone duration presented, high accuracy in discriminating the two tone durations was required before the pigeons could discriminate the different reinforcement schedules and then respond in accordance with the obtained relative rates of reinforcement (see Davison & Tustin, 1978, and McCarthy & Davison, 1979, who make a similar point). Most previous signal-detection experiments that have varied payoffs have used reinforcement that differed for hits and correct rejections, so that high accuracy would work against responding in accordance with the different reinforcement schedules. High accuracy is by definition responding that is controlled by the required discrimination. In the present experiment the tone-duration discrimination was not made very easy, as this might have resulted in ceiling effects that would have hin-

dered observations of changes in signal detection theory's index of sensitivity as the VI schedule for incorrect responses was changed.

Second, matching law response bias,  $k$ , was usually greater than the ideal value of 1.0 in this experiment. However, in the usual matching-law experiment, response bias stands for response bias for the left or right response alternative. Great care is taken to ensure that responses on these two alternatives are equal in difficulty and such efforts are often successful (Baum, 1974). Here response bias stands for response bias for the alternative with the short (correct) VI schedule as compared with the alternative with the long (incorrect) VI schedule. A constant response bias for the short VI schedule key was found. This corresponds to Davison and Tustin's (1978) finding that there is a bias to respond on the alternative associated with the presented stimulus (i.e., on the "correct" alternative).

By definition the parameter called response bias in a matching-law analysis,  $k$ , represents response bias that is constant throughout the experiment, and so a matching-law analysis yields only one value for  $k$  as VI schedules are varied. For the matching law, the effects of changing relative reinforcement are expressed as changes in response distribution (the response ratio), not bias. Therefore in the matching-law analysis, there were relatively more responses or time spent on the incorrect alternative as the relative reinforcement rate for those responses was increased. This is indicated by the fact that 22 out of 24 of the best fitting lines in Figures 10 and 11 are of a positive slope.

Figures 10 and 11 appear to show that the matching-law measure of discriminability,  $a$ , the slope of the lines, also did not change as the VI schedule for incorrect responses was changed, otherwise the data would follow a curve with the slope decreasing as 0 ( $\log 1.0$ ) is approached on the x-axis. This is explained by the fact that  $a$  is a scaling parameter that takes the difference between the rates of reinforcement for correct and incorrect responses and scales these differences; responses are in accordance with the scaled differences. Therefore changing the VI schedules themselves would not influence  $a$ , whereas changing the difficulty of the discrimination that tells a subject which VI is on which response alternative would influence  $a$ . A subject in a matching-law

experiment uses the tone durations as information concerning the location of the VI schedules.

Results obtained from the signal-detection analysis were consistent with Davison and McCarthy's (1980) matching-model of signal detection and were similar to those obtained in traditional signal-detection experiments. Increasing the difficulty of the tone-duration discrimination decreased signal detection's measure of sensitivity,  $A'$ , while leaving its measure of bias,  $B''$ , unchanged. Changing the distribution of reinforcement for correct and incorrect responses likewise did not affect  $B''$ , which measures bias for the red or the green key.

In addition, as the incorrect VI schedule was made more similar to the correct VI schedule,  $A'$  decreased. This is contrary to traditional signal-detection theory (Green & Swets, 1966) but entirely consistent with data obtained in similar experiments (Nevin, 1970; Nevin et al., 1975; Nevin et al., Note 1). In the present experiment increasing reinforcement for incorrect responses probably decreased signal-detection sensitivity because correct and incorrect responses were defined by the presence of reinforcement for correct responses and the absence of reinforcement for incorrect responses (see Nevin et al., 1975, for further discussion of why reinforcement for errors decreases sensitivity). As this distinction began to break down, the actual discrimination between the short- and long-duration tones became increasingly less important, in effect resulting in a decrease in sensitivity. When errors are reinforced, maintaining a high value of  $A'$  actually reduces total reinforcement (cf. optimality theory; see, e.g., Rachlin, Kagel, & Battalio, 1980).

Comparing the data recorded only until the first changeover (or until the end of a trial if there were no changeovers) provides further information with regard to the matching law's and signal detection's analyses of choice. Both matching-law discriminability,  $a$ , and signal-detection sensitivity,  $A'$ , were greater for data collected prior to the first changeover, while matching-law response bias,  $k$ , tended to change from greater than 1.0 to closer to 1.0 (9 out of 12 cases), and signal detection bias,  $B''$ , showed no change. This indicates that the pigeons' discrimination between the short and long tones was better during the earlier parts of the trials. The parameter  $A'$  is a direct measure of this better discrimination. The param-

eter  $a$ , on the other hand, measures discriminability between the VI schedules for correct and incorrect responses. As explained above, the tone-duration discrimination is a prerequisite for the VI-schedule discrimination. A better tone-duration discrimination permits the subjects to distribute their responses more in line with the distribution of reinforcers, showing less of a bias for the "correct" key and therefore a decrease in  $k$ . However it is not then clear why  $k$  remained the same when the tone-duration discrimination was made more difficult. It is possible that this lack of change was due to a ceiling effect; the values of  $k$  obtained with the initial tone-duration discrimination were already high and could possibly go no higher when that discrimination was made more difficult.

With respect to signal detection's measure of bias,  $B''$ , although an increased tendency to make a correct response prior to the first changeover will affect the total distribution of correct and incorrect responses, it will not affect the total distribution of short- or long-tone responses. In terms of Figure 3, the totals for the red-key and green-key response rows will not change; the actual values in each of the four cells will change. Since signal detection's measure of bias,  $B''$ , is based on the subject's tendency to emit a signal (red-key) or noise (green-key) response,  $B''$  does not differ prior to the first changeover. The fact that the tone-duration discrimination was better during the first parts of the trials (on shorter trials) is consistent with much other evidence showing that discrimination is poorer following a retention interval (see, e.g., McCarthy, Davison, & Jenkins, 1982; Rilling & Howard, 1981).

## CONCLUSION

The present experiment has attempted to clarify some of the similarities and differences between the matching-law and signal-detection methods of analyzing choice, as well as to examine these methods in a more general procedural context. Both methods are concerned with responding determined by discriminations between stimuli and by the payoffs for different responses. The data reported here have shown that it is possible to investigate the matching law and signal-detection theory within a single experiment whose design is

easily acceptable to theorists working in either area.

Investigation of the matching law has generally meant the use of free-operant procedures, whereas signal-detection experiments employ discrete trials. Yet the data obtained from a signal-detection analysis of the present free-operant experiment are entirely consistent with those obtained in previous signal-detection experiments. Despite the decrease in discrimination with time since the stimuli to be discriminated were presented, results were orderly when all responses were used in the analyses (cf. Blough, 1965).

Investigation of signal-detection theory has generally meant the use of an explicit discrimination that was followed by differential payoffs for correct and incorrect responses, whereas matching-law experiments have involved only differential reinforcement for different types of responses. Yet the data obtained in the present experiment are also consistent with those obtained in previous traditional matching-law experiments. The explicit discrimination used here functioned to limit the subjects' discrimination of the reinforcement schedules. Were the subjects' tone-duration discrimination perfect or were there no tone-duration discrimination as in the traditional matching-law experiments, determination of the subjects' responses by the reinforcer distribution would still be limited by discrimination of that distribution. Clearly the size of *a* is strongly affected by the procedure of an experiment. This suggests that it may be futile to search for the one value of *a* remaining after all random error is removed (see Baum, 1979).

The present experiment also provides further information relevant to recent attempts to integrate the matching-law and signal-detection analyses of choice in one quantitative choice model (e.g., McCarthy & Davison, 1981; Nevin et al., 1982). First, free-operant procedures can be used to examine these models. The decrease in signal-detection sensitivity (e.g., *A'*) with reinforcement for errors is a robust phenomenon, having now been obtained with the present free-operant, as well as previous discrete-trial, procedures (e.g., Nevin et al., 1975). Further efforts to account for that effect will be of value.

Second, the analyses in the present experiment have clearly demonstrated what has been apparent to the model builders for some time—

that the matching law and signal detection were but two ways of looking at a common problem: choice. It has been possible to analyze data from both perspectives using a data set fairly similar to those obtained from either matching-law or signal-detection experiments. Relationships between the two methods of analysis can therefore be seen more easily. For example, the matching law response distribution of correct divided by incorrect responses ( $B_1/B_2$  in Equation 1) was affected similarly by changes in reinforcement for errors as was *A'*. Both measures increased as relative reinforcement for errors decreased. This is not surprising as *A'* is a transformation of correct/incorrect responses and of  $\log d$  and of percentage of correct responses (see Figure 2) as well. Matching-law researchers should now be better able to observe this fact.

Finally, the present results can be used to make recommendations for which method of analysis, the matching law or signal detection, should be used in analyzing data from a particular experiment on choice. Table 2 shows that since changes in difficulty of discrimination can be observed immediately with signal-detection theory by monitoring *A'*, and the same changes can be monitored within the context of the matching law only after running several different reinforcement conditions and measuring *a*, it is more efficient to study the effects of changing the difficulty of a discrimination by using a signal-detection analysis. With respect to the effects of different frequencies of payoffs on responses, however, a matching-law analysis may be easier to comprehend because only response distribution changes, whereas in a signal-detection analysis either *A'* or *B''* can change depending on the payoff matrix.

Table 2  
Data Summary

Experimental Manipulation	Signal Detection		Matching Law	
	Sensitivity <i>A'</i>	Bias <i>B''</i>	Discriminability <i>a</i>	Response Bias <i>k</i>
Harder discrimination	decreased	no change	decreased	no change
Increased relative reinforcement for incorrect responses	decreased	no change	no change	no change
Prior to first changeover	increased	no change	increased	decreased



## REFERENCE NOTE

1. Nevin, J. A., Jenkins, P., Whittaker, S., & Yarensky, P. *Signal detection and matching*. Paper presented at the meeting of the Psychonomic Society, November, 1977.

## REFERENCES

- Baum, W. M. On two types of deviation from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior*, 1974, **22**, 231-242.
- Baum, W. M. Matching, undermatching, and overmatching in studies of choice. *Journal of the Experimental Analysis of Behavior*, 1979, **32**, 269-281.
- Blough, D. S. Definition and measurement in generalization research. In D. I. Mostofsky (Ed.), *Stimulus generalization*. Stanford, Calif.: Stanford University Press, 1965.
- Bourland, G., & Miller, J. T. The role of discriminative stimuli in concurrent performances. *Journal of the Experimental Analysis of Behavior*, 1981, **36**, 231-239.
- Clopton, B. M. Detection of increments in noise intensity by monkeys. *Journal of the Experimental Analysis of Behavior*, 1972, **17**, 473-481.
- Davenport, W. G. Auditory vigilance: The effects of costs and values on signals. *Australian Journal of Psychology*, 1968, **20**, 213-218.
- Davenport, W. G. Vibrotactile vigilance: The effects of costs and values on signals. *Perception and Psychophysics*, 1969, **5**, 25-28.
- Davison, M., & McCarthy, D. Reinforcement for errors in a signal-detection procedure. *Journal of the Experimental Analysis of Behavior*, 1980, **34**, 35-47.
- Davison, M. C., & Tustin, R. D. The relation between the generalized matching law and signal-detection theory. *Journal of the Experimental Analysis of Behavior*, 1978, **29**, 331-336.
- de Villiers, P. Choice in concurrent schedules and a quantitative formulation of the law of effect. In W. K. Honig & J. E. R. Staddon (Eds.), *Handbook of operant behavior*. Englewood Cliffs, N.J.: Prentice-Hall, 1977.
- Elmore, T. F. Duration discrimination: Effects of probability of stimulus presentation. *Journal of the Experimental Analysis of Behavior*, 1972, **18**, 465-469.
- Fleshler, M., & Hoffman, H. S. A progression for generating variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, 1962, **5**, 529-530.
- Green, D. M., & Swets, J. A. *Signal detection theory and psychophysics*. New York: Wiley, 1966. (Reprinted by Robert E. Krieger, 1974.)
- Grier, J. B. Nonparametric indexes for sensitivity and bias: Computing formulas. *Psychological Bulletin*, 1971, **75**, 424-429.
- Herrnstein, R. J. Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior*, 1961, **4**, 267-272.
- Herrnstein, R. J. On the law of effect. *Journal of the Experimental Analysis of Behavior*, 1970, **13**, 243-266.
- Hobson, S. L. Discriminability of fixed-ratio schedules for pigeons: Effects of payoff values. *Journal of the Experimental Analysis of Behavior*, 1978, **30**, 69-81.
- Hume, A. L., & Irwin, R. J. Bias functions and operating characteristics of rats discriminating auditory stimuli. *Journal of the Experimental Analysis of Behavior*, 1974, **21**, 285-295.
- Killeen, P. R. Superstition: A matter of bias, not detectability. *Science*, 1978, **199**, 88-90.
- Kinchla, J. Discrimination of two auditory durations by pigeons. *Perception and Psychophysics*, 1970, **8**, 299-307.
- Lattal, K. A. Reinforcement contingencies as discriminative stimuli: II. Effects of changes in stimulus probability. *Journal of the Experimental Analysis of Behavior*, 1979, **31**, 15-22.
- Mandell, C. A psychophysical analysis of time-based schedules of reinforcement. In M. L. Commons & J. A. Nevin (Eds.), *Quantitative analyses of behavior* (Vol. 1). *Discriminative properties of reinforcement schedules*. Cambridge, Mass.: Ballinger, 1981.
- McCarthy, D., & Davison, M. Signal probability, reinforcement and signal detection. *Journal of the Experimental Analysis of Behavior*, 1979, **32**, 373-386.
- McCarthy, D., & Davison, M. Independence of sensitivity to relative reinforcement rate and discriminability in signal detection. *Journal of the Experimental Analysis of Behavior*, 1980, **34**, 272-284. (a)
- McCarthy, D., & Davison, M. On the discriminability of stimulus duration. *Journal of the Experimental Analysis of Behavior*, 1980, **33**, 187-211. (b)
- McCarthy, D., & Davison, M. Towards a behavioral theory of bias in signal detection. *Perception and Psychophysics*, 1981, **29**, 371-382.
- McCarthy, D., Davison, M., & Jenkins, P. E. Stimulus discriminability in free-operant and discrete-trial detection procedures. *Journal of the Experimental Analysis of Behavior*, 1982, **37**, 199-215.
- Miller, J. T., Saunders, S. S., & Bourland, G. The role of stimulus disparity in concurrently available reinforcement schedules. *Animal Learning and Behavior*, 1980, **8**, 635-641.
- Nevin, J. A. Effects of reinforcement scheduling on simultaneous discrimination performance. *Journal of the Experimental Analysis of Behavior*, 1967, **10**, 251-260.
- Nevin, J. A. Interval reinforcement of choice behavior in discrete trials. *Journal of the Experimental Analysis of Behavior*, 1969, **12**, 875-885. (a)
- Nevin, J. A. Signal detection theory and operant behavior: A review of David M. Green and John A. Swets' *Signal detection theory and psychophysics*. *Journal of the Experimental Analysis of Behavior*, 1969, **12**, 474-480. (b)
- Nevin, J. A. On differential stimulation and differential reinforcement. In W. C. Stebbins (Ed.), *Animal psychophysics*. New York: Appleton-Century-Crofts, 1970.
- Nevin, J. A., Jenkins, P., Whittaker, S., & Yarensky, P. Reinforcement contingencies and signal detection. *Journal of the Experimental Analysis of Behavior*, 1982, **37**, 65-79.
- Nevin, J. A., Olson, K., Mandell, C., & Yarensky, P. Differential reinforcement and signal detection. *Journal of the Experimental Analysis of Behavior*, 1975, **24**, 355-367.

- Pastore, R. E., & Scheirer, C. J. Signal detection theory: Considerations for general application. *Psychological Bulletin*, 1974, **81**, 945-958.
- Rachlin, H., Kagel, J. H., & Battalio, R. C. Substitutability in time allocation. *Psychological Review*, 1980, **87**, 355-374.
- Rilling, M., & Howard, R. C. The analysis of memory for signals and food in a successive discrimination. In M. L. Commons & J. A. Nevin (Eds.), *Quantitative analyses of behavior* (Vol. 1). *Discriminative properties of reinforcement schedules*. Cambridge, Mass.: Ballinger, 1981.
- Rilling, M., & McDiarmid, C. Signal detection in fixed-ratio schedules. *Science*, 1965, **148**, 526-527.
- Shimp, C. P. Probabilistically reinforced choice behavior in pigeons. *Journal of the Experimental Analysis of Behavior*, 1966, **9**, 443-455.
- Snedecor, G. W., & Cochran, W. G. *Statistical methods*. Ames, Iowa: Iowa State University Press, 1967.
- Staddon, J. E. R. Theory of behavioral power functions. *Psychological Review*, 1978, **85**, 305-320.
- Stevens, S. S. On the psychophysical law. *Psychological Review*, 1957, **64**, 153-181.
- Stubbs, A. The discrimination of stimulus duration by pigeons. *Journal of the Experimental Analysis of Behavior*, 1968, **11**, 223-238.
- 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)
- Swets, J. A., Tanner, W. P., & Birdsall, T. G. Decision processes in perception. *Psychological Review*, 1961, **68**, 301-340.
- Terman, M., & Terman, J. S. Concurrent variation of response bias and sensitivity in an operant-psychophysical test. *Perception and Psychophysics*, 1972, **11**, 428-432.
- Wright, A. A. Psychometric and psychophysical hue discrimination functions for the pigeon. *Vision Research*, 1972, **12**, 1447-1464.
- Wright, A. A., & Nevin, J. A. Signal detection methods for measurement of utility in animals. *Journal of the Experimental Analysis of Behavior*, 1974, **21**, 373-380.

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#### APPENDIX

The number of responses, time spent pecking, and the number of reinforcers received for responses for each subject. Data presented are the means and standard errors (in parentheses) of the last five days of each condition. Both whole-trial and until the first change-over data are shown. A hit is defined as a peck on the red key following presentation of the short tone, a correct rejection as a peck on the green key following presentation of the long tone, a false alarm as a peck on the red key following presentation of the long tone, and a miss as a peck on the green key following presentation of the short tone.

Tone		Responses				Time				Reinforcers			
Durations	Incorrect	Hits	CRs	FAs	Misses	Hits	CRs	FAs	Misses	Hits	CRs	FAs	Misses
(sec/sec)	VI												
Subject 1—Whole-Trial Data													
2/10	extinction	218.4 (12.5)	274.2 (12.1)	59.4 (9.4)	121.4 (13.5)	1.4 (.1)	1.5 (.1)	.7 (.1)	.9 (.1)	24.2 (1.5)	25.8 (1.5)	0.0 (0.0)	0.0 (0.0)
2/10	120-sec	246.2 (11.4)	204.2 (7.0)	30.4 (7.1)	52.0 (5.2)	1.8 (.1)	1.3 (.1)	.3 (.1)	.5 (.1)	26.4 (1.2)	22.0 (1.2)	.6 (.2)	1.0 (.5)
2/10	60-sec	202.0 (9.1)	249.4 (12.9)	21.6 (7.6)	48.4 (10.1)	1.5 (.1)	1.6 (.1)	.2 (.1)	.4 (.1)	25.0 (1.2)	22.8 (1.2)	.4 (.2)	1.8 (.2)
2/10	30-sec	216.8 (15.7)	207.6 (9.0)	43.2 (9.5)	37.4 (11.3)	1.4 (.1)	1.5 (.1)	.3 (.1)	.3 (.1)	23.8 (1.4)	21.4 (1.2)	2.8 (.7)	2.0 (.5)
2/10	15-sec	183.6 (15.2)	183.0 (21.5)	51.4 (5.9)	89.2 (10.5)	1.2 (.1)	1.2 (.1)	.3 (.0)	.6 (.1)	19.8 (1.5)	18.6 (1.7)	4.6 (1.0)	7.0 (1.2)
2/10	7.5-sec	155.8 (16.9)	172.2 (22.6)	39.2 (5.7)	66.8 (8.3)	1.0 (.1)	1.1 (.1)	.2 (.0)	.4 (.1)	16.8 (2.2)	18.6 (2.3)	5.8 (.8)	8.8 (.7)
2/10	5-sec	108.6 (8.1)	182.4 (6.1)	58.4 (6.7)	67.8 (3.7)	.7 (.1)	1.2 (.1)	.3 (.0)	.4 (.0)	13.8 (1.1)	17.8 (.9)	8.4 (1.1)	10.0 (1.0)
2/10	7.5-sec	138.6 (6.6)	158.8 (2.0)	65.0 (4.3)	68.4 (3.9)	.8 (.1)	1.0 (.1)	.4 (.0)	.5 (.0)	16.6 (.9)	17.4 (1.0)	8.0 (.9)	8.0 (1.0)
2/10	15-sec	145.8 (5.6)	191.4 (9.2)	44.0 (7.2)	92.2 (14.4)	1.0 (.1)	1.2 (.1)	.3 (.0)	.6 (.1)	16.4 (.4)	21.4 (.6)	4.0 (.9)	8.2 (1.3)
2/10	30-sec	185.8 (16.3)	208.6 (19.1)	50.4 (12.7)	65.4 (8.4)	1.2 (.1)	1.3 (.1)	.4 (.1)	.4 (.1)	21.8 (1.5)	21.6 (1.1)	2.8 (1.0)	3.8 (.4)
2/10	60-sec	207.0 (9.0)	239.4 (10.9)	18.6 (3.9)	41.8 (7.9)	1.4 (.1)	1.7 (.1)	.1 (.0)	.3 (.1)	21.6 (.6)	24.6 (.6)	1.6 (.5)	2.2 (.4)
3/9	60-sec	191.2 (12.3)	212.6 (10.9)	44.4 (10.8)	64.6 (7.6)	1.3 (.1)	1.4 (.1)	.3 (.1)	.5 (.1)	20.2 (1.1)	23.8 (1.0)	2.6 (.5)	3.4 (.6)
3/9	30-sec	196.4 (17.3)	198.0 (13.1)	54.8 (4.8)	33.4 (5.6)	1.4 (.2)	1.4 (.1)	.4 (.1)	.2 (.1)	21.8 (1.0)	21.0 (1.0)	4.4 (.5)	2.8 (.3)
3/9	15-sec	202.0	169.2	35.6	44.2	1.5	1.1	.3	.3	21.6	20.8	3.2	4.4

APPENDIX (continued)

Tone Durations Incorrect (sec/sec)		Responses				Time				Reinforcers			
	VI	Hits	CRs	FAs	Misses	Hits	CRs	FAs	Misses	Hits	CRs	FAs	Misses
3/9	30-sec	(17.3) 157.4	(11.0) 234.6	(8.0) 24.8	(7.0) 55.0	(.1) 1.2	(.1) 1.6	(.1) .2	(.1) .5	(1.8) 19.0	(1.8) 24.8	(.3) 3.0	(.5) 3.2
		(6.9)	(10.1)	(5.9)	(7.3)	(.0)	(.1)	(.1)	(.1)	(1.1)	(1.6)	(.6)	(.8)
3/9	60-sec	218.8	196.2	27.0	73.0	1.6	1.2	.2	.5	24.0	22.0	.8	3.2
		(13.8)	(9.4)	(4.5)	(3.6)	(.1)	(.1)	(.0)	(.0)	(.9)	(.9)	(.3)	(.7)
3/9	120-sec	223.8	242.6	35.8	72.0	1.5	1.6	.3	.6	24.0	24.8	.4	.8
		(14.3)	(17.9)	(6.9)	(7.0)	(.1)	(.1)	(.1)	(.1)	(1.2)	(1.0)	(.2)	(.3)
<i>Subject 1—Data Until First Changeover</i>													
2/10	extinction	133.2	221.6	24.6	56.0	.9	1.3	.4	.4				
		(13.1)	(9.9)	(7.5)	(14.3)	(.1)	(.0)	(.2)	(.1)				
2/10	120-sec	202.6	186.6	8.4	23.2	1.5	1.2	.1	.2	20.6	19.2	.0	.6
		(15.0)	(5.8)	(4.6)	(5.6)	(.1)	(.0)	(.1)	(.1)	(1.3)	(1.2)	(.0)	(.4)
2/10	60-sec	176.8	240.8	10.8	32.6	1.4	1.6	.1	.3	21.2	21.0	.0	.8
		(9.2)	(13.7)	(5.9)	(11.4)	(.1)	(.1)	(.1)	(.1)	(1.2)	(1.3)	(.0)	(.2)
2/10	30-sec	197.4	188.2	18.6	17.6	1.3	1.4	.2	.2	21.0	18.6	1.2	.2
		(8.4)	(9.8)	(5.5)	(5.5)	(.1)	(.1)	(.1)	(.1)	(.8)	(1.4)	(.5)	(.2)
2/10	15-sec	134.8	156.6	20.6	27.4	.9	1.0	.2	.2	13.8	15.2	1.8	1.4
		(12.2)	(20.8)	(3.7)	(4.4)	(.1)	(.1)	(.0)	(.0)	(1.2)	(2.0)	(.9)	(.6)
2/10	7.5-sec	137.0	157.2	16.4	11.0	.9	1.0	.1	.1	14.6	17.0	2.0	1.6
		(14.6)	(21.4)	(3.8)	(2.6)	(.1)	(.1)	(.0)	(.0)	(2.0)	(2.1)	(.8)	(.4)
2/10	5-sec	97.2	169.6	21.4	41.4	.7	1.1	.1	.2	11.4	16.2	3.0	5.4
		(5.4)	(6.4)	(6.0)	(3.4)	(.1)	(.1)	(.0)	(.0)	(.7)	(1.0)	(.8)	(1.2)
2/10	7.5-sec	98.0	133.6	30.6	37.8	.6	.9	.2	.3	12.2	14.4	2.4	3.0
		(7.3)	(4.5)	(4.4)	(7.9)	(.1)	(.1)	(.0)	(.1)	(.9)	(.9)	(.4)	(1.0)
2/10	15-sec	99.6	171.8	7.6	44.2	.7	1.1	.1	.3	10.6	18.4	.6	3.8
		(4.7)	(8.5)	(4.7)	(9.7)	(.0)	(.1)	(.0)	(.1)	(1.3)	(.7)	(.5)	(.8)
2/10	30-sec	145.4	171.8	20.8	24.2	1.0	1.1	.1	1.5	16.4	17.2	1.4	1.2
		(12.9)	(23.5)	(14.0)	(4.9)	(.1)	(.2)	(.1)	(1.2)	(1.0)	(2.4)	(.7)	(.3)
2/10	60-sec	178.8	229.0	2.4	15.8	1.2	1.6	.0	.1	17.8	23.0	.6	.4
		(11.8)	(8.2)	(.9)	(7.9)	(.1)	(.1)	(.0)	(.1)	(.7)	(.4)	(.2)	(.2)
3/9	60-sec	166.8	184.4	12.6	17.4	1.2	1.2	.1	.3	16.6	20.4	1.0	1.2
		(11.1)	(5.3)	(3.4)	(7.8)	(.1)	(.1)	(.0)	(.1)	(.9)	(.8)	(.3)	(.3)
3/9	30-sec	184.2	173.8	9.4	19.0	1.4	1.2	.1	.2	19.4	17.2	.8	1.4
		(17.6)	(13.4)	(3.5)	(4.7)	(.2)	(.1)	(.0)	(.0)	(1.2)	(1.3)	(.3)	(.6)
3/9	15-sec	187.8	161.0	16.6	30.0	1.4	1.1	.2	.2	19.4	19.6	.8	2.6
		(17.8)	(8.3)	(6.8)	(6.0)	(.2)	(.1)	(.1)	(.1)	(1.8)	(1.7)	(.3)	(.6)
3/9	30-sec	136.6	223.8	5.6	30.8	1.1	1.5	.1	.3	15.2	23.4	.6	1.0
		(9.4)	(12.7)	(2.5)	(8.3)	(.0)	(.1)	(.0)	(.1)	(1.5)	(1.8)	(.2)	(.3)
3/9	60-sec	159.6	181.4	10.8	41.0	1.3	1.1	.1	.3	16.4	19.4	.4	1.6
		(14.5)	(11.9)	(3.2)	(7.7)	(.1)	(.1)	(.0)	(.1)	(1.4)	(1.1)	(.2)	(.8)
3/9	120-sec	167.2	211.2	4.6	28.2	1.2	1.5	.0	.3	16.0	20.4	.2	.4
		(8.7)	(21.2)	(2.7)	(3.8)	(.1)	(.2)	(.0)	(.0)	(1.1)	(1.3)	(.2)	(.2)
<i>Subject 2—Whole-Trial Data</i>													
2/10	extinction	194.6	220.6	84.0	108.6	1.1	1.3	.7	.9	24.8	25.2	.0	.0
		(14.9)	(19.1)	(4.1)	(10.3)	(.2)	(.3)	(.1)	(.2)	(1.3)	(1.3)	(.0)	(.0)
2/10	120-sec	203.6	184.2	139.4	97.8	1.2	1.3	1.2	1.0	24.4	22.4	1.6	1.6
		(18.8)	(19.7)	(20.4)	(5.6)	(.1)	(.2)	(.2)	(.1)	(1.2)	(1.2)	(.5)	(.5)
2/10	60-sec	187.2	205.4	113.6	70.8	1.3	1.3	1.0	.6	22.4	23.0	2.0	2.6
		(15.9)	(25.1)	(23.6)	(10.7)	(.2)	(.2)	(.2)	(.1)	(1.6)	(2.0)	(.8)	(.5)
2/10	30-sec	200.0	186.2	73.8	42.4	1.5	1.2	.6	.3	24.2	18.2	5.0	2.6
		(13.7)	(11.9)	(7.4)	(6.8)	(.1)	(.1)	(.1)	(.1)	(.9)	(1.2)	(1.0)	(.6)
2/10	15-sec	148.0	160.4	81.4	27.2	1.2	1.1	.7	.2	19.2	19.8	7.2	3.8
		(6.0)	(17.3)	(11.6)	(6.1)	(.1)	(.1)	(.1)	(.1)	(.7)	(1.1)	(.5)	(.7)
2/10	7.5-sec	166.4	104.4	107.4	19.4	1.3	.7	.9	.1	20.2	13.2	13.2	3.4
		(19.8)	(16.4)	(13.4)	(2.4)	(.2)	(.1)	(.2)	(.0)	(2.2)	(1.5)	(1.4)	(.5)
2/10	5-sec	178.2	75.2	79.6	22.0	1.3	.5	.5	.1	22.2	9.8	13.8	4.2
		(12.5)	(14.4)	(6.9)	(4.4)	(.1)	(.1)	(.1)	(.0)	(1.2)	(1.4)	(.9)	(.3)
2/10	7.5-sec	182.0	89.8	104.6	27.2	1.3	.6	.9	.2	20.6	10.8	15.2	3.4
		(12.4)	(11.0)	(20.5)	(5.6)	(.1)	(.1)	(.1)	(.1)	(1.0)	(1.1)	(.8)	(.4)
2/10	15-sec	219.4	152.0	101.4	81.8	1.6	.9	.9	.6	26.4	18.4	8.2	7.0
		(28.4)	(31.1)	(13.9)	(25.1)	(.1)	(.2)	(.2)	(.2)	(3.6)	(2.9)	(1.3)	(2.4)

## APPENDIX (continued)

Tone Durations (sec/sec)	Incorrect VI	Responses				Time				Reinforcers			
		Hits	CRs	FAs	Misses	Hits	CRs	FAs	Misses	Hits	CRs	FAs	Misses
2/10	30-sec	207.6 (7.5)	146.4 (10.7)	104.4 (9.0)	69.8 (7.4)	1.4 (.1)	.9 (.1)	.9 (.1)	.6 (.1)	24.0 (1.4)	18.6 (1.6)	5.0 (1.1)	2.4 (.8)
2/10	60-sec	222.0 (5.3)	187.2 (7.6)	80.8 (10.2)	106.2 (9.6)	1.3 (.1)	1.1 (.1)	.7 (.1)	.9 (.1)	24.8 (.5)	21.0 (1.1)	2.0 (.8)	2.2 (.6)
3/9	60-sec	214.6 (15.5)	185.6 (6.4)	112.8 (9.7)	146.4 (9.5)	1.2 (.1)	1.1 (.0)	.9 (.1)	1.1 (.1)	25.8 (.9)	20.4 (.7)	2.0 (.3)	1.8 (.6)
3/9	30-sec	182.2 (14.3)	142.0 (8.8)	122.8 (14.5)	84.2 (9.0)	1.2 (.1)	1.0 (.1)	1.1 (.1)	.8 (.1)	20.4 (1.4)	20.0 (1.7)	6.2 (.4)	3.4 (.5)
3/9	15-sec	141.2 (16.1)	138.6 (8.6)	144.6 (11.7)	57.0 (7.9)	.9 (.1)	.9 (.1)	1.2 (.1)	.4 (.1)	18.4 (1.2)	17.2 (.5)	10.0 (.6)	4.4 (.8)
3/9	30-sec	159.0 (10.5)	141.2 (9.3)	97.6 (2.6)	126.8 (9.2)	1.1 (.1)	1.0 (.1)	.8 (.0)	1.1 (.1)	21.6 (1.8)	20.2 (1.7)	3.6 (.5)	4.6 (.9)
3/9	60-sec	173.4 (12.4)	183.4 (19.6)	121.6 (18.4)	76.8 (6.4)	1.1 (.1)	1.3 (.1)	1.1 (.2)	.7 (.0)	23.0 (1.0)	22.0 (1.4)	2.8 (.8)	2.2 (.8)
3/9	120-sec	187.6 (10.3)	191.4 (12.3)	115.2 (4.5)	71.6 (10.4)	1.5 (.1)	1.4 (.1)	1.1 (.1)	.7 (.1)	25.0 (1.3)	22.4 (1.0)	1.4 (.4)	1.2 (.5)
<i>Subject 2—Data Until First Changeover</i>													
2/10	extinction	116.8 (11.5)	150.0 (17.4)	30.4 (1.7)	55.6 (6.8)	.8 (.1)	1.1 (.1)	.4 (.0)	.5 (.1)				
2/10	120-sec	118.6 (12.5)	94.8 (9.8)	58.8 (5.5)	33.0 (7.3)	.7 (.1)	.8 (.1)	.5 (.0)	.4 (.1)	12.8 (.8)	8.0 (1.3)	.8 (.3)	.0 (.0)
2/10	60-sec	146.4 (11.0)	142.2 (15.6)	55.8 (16.0)	21.2 (4.7)	1.0 (.1)	1.0 (.1)	.5 (.2)	.2 (.1)	16.0 (1.5)	13.8 (1.2)	.8 (.3)	.4 (.2)
2/10	30-sec	173.0 (12.7)	144.4 (9.9)	28.4 (5.3)	11.2 (2.9)	1.3 (.1)	1.0 (.1)	.3 (.1)	.1 (.0)	20.6 (.8)	12.0 (1.6)	1.2 (.5)	.6 (.2)
2/10	15-sec	143.2 (5.0)	127.0 (14.9)	56.2 (7.2)	8.2 (3.8)	1.2 (.1)	.9 (.1)	.5 (.1)	.1 (.0)	18.2 (.9)	14.0 (.9)	4.8 (.5)	.2 (.2)
2/10	7.5-sec	163.8 (19.4)	81.2 (15.8)	93.4 (13.7)	.4 (.4)	1.3 (.2)	.5 (.1)	.8 (.2)	.0 (.0)	19.6 (2.1)	8.6 (1.4)	11.2 (1.6)	.2 (.2)
2/10	5-sec	175.0 (14.3)	65.6 (12.4)	74.0 (7.6)	4.8 (2.7)	1.3 (.1)	.4 (.1)	.5 (.1)	.0 (.0)	22.0 (1.1)	7.6 (1.0)	12.4 (.6)	.4 (.2)
2/10	7.5-sec	173.4 (14.4)	72.2 (12.2)	109.2 (10.5)	6.6 (4.7)	1.2 (.1)	.5 (.1)	.8 (.1)	.0 (.0)	19.8 (1.1)	7.4 (1.4)	13.6 (.7)	.6 (.4)
2/10	15-sec	191.2 (18.6)	113.4 (31.4)	79.8 (11.6)	49.6 (16.5)	1.5 (.1)	.7 (.2)	.7 (.2)	.4 (.1)	21.0 (1.3)	12.2 (3.1)	6.2 (.8)	3.4 (1.2)
2/10	30-sec	163.0 (8.5)	90.0 (9.8)	72.4 (6.1)	29.6 (5.6)	1.1 (.1)	.6 (.1)	.7 (.1)	.3 (.0)	17.6 (1.7)	9.8 (1.8)	3.6 (1.0)	1.2 (.7)
2/10	60-sec	157.8 (4.9)	124.8 (6.9)	39.6 (9.7)	54.8 (10.3)	1.0 (.0)	.7 (.1)	.4 (.1)	.5 (.1)	14.8 (.4)	12.2 (.9)	.8 (.3)	1.0 (.7)
3/9	60-sec	88.8 (9.2)	113.2 (12.3)	34.4 (8.0)	86.2 (7.7)	.5 (.1)	.7 (.1)	.3 (.1)	.7 (.1)	9.0 (.8)	9.8 (.6)	.6 (.2)	1.0 (.5)
3/9	30-sec	127.0 (11.3)	82.8 (7.6)	87.6 (10.9)	26.4 (4.5)	.8 (.1)	.6 (.1)	.8 (.1)	.2 (.1)	13.8 (1.0)	8.4 (1.2)	4.0 (.6)	.6 (.2)
3/9	15-sec	121.8 (14.6)	94.0 (7.8)	102.8 (11.1)	48.6 (8.0)	.8 (.1)	.6 (.1)	.8 (.1)	.4 (.1)	14.2 (1.4)	9.8 (.3)	6.2 (.5)	3.0 (1.0)
3/9	30-sec	109.2 (7.9)	81.2 (8.0)	68.6 (6.1)	90.8 (8.6)	.8 (.1)	.6 (.1)	.5 (.0)	.8 (.1)	12.8 (1.3)	9.0 (.9)	2.0 (.6)	2.8 (.7)
3/9	60-sec	138.4 (11.0)	108.6 (17.9)	72.8 (15.9)	42.4 (5.9)	.9 (.1)	.8 (.2)	.7 (.2)	.4 (.1)	16.6 (1.2)	10.0 (1.7)	1.6 (.6)	.6 (.2)
3/9	120-sec	156.6 (13.6)	135.8 (14.4)	46.0 (4.0)	53.8 (10.3)	1.3 (.2)	1.0 (.1)	.5 (.1)	.5 (.1)	19.0 (1.8)	13.2 (1.7)	.2 (.2)	.6 (.2)
<i>Subject 3—Whole-Trial Data</i>													
2/10	extinction	166.6 (15.2)	194.6 (14.2)	57.4 (4.5)	42.2 (7.6)	1.4 (.1)	1.6 (.2)	.8 (.1)	.6 (.1)	24.6 (1.2)	25.4 (1.2)	.0 (.0)	.0 (.0)
2/10	120-sec	146.0 (10.1)	196.8 (12.9)	32.4 (7.8)	38.6 (7.5)	1.5 (.1)	1.6 (.1)	.4 (.1)	.4 (.1)	24.2 (2.0)	24.6 (2.0)	.8 (.2)	.4 (.2)
2/10	60-sec	134.0 (19.0)	150.8 (11.1)	39.4 (12.0)	65.6 (13.5)	1.4 (.1)	1.2 (.1)	.5 (.2)	.7 (.2)	21.4 (.7)	23.4 (1.3)	2.2 (.6)	3.0 (1.1)
2/10	30-sec	147.2 (12.5)	154.6 (11.9)	70.2 (14.2)	33.0 (10.0)	1.5 (.1)	1.2 (.1)	.8 (.2)	.3 (.1)	22.6 (1.7)	20.2 (1.1)	5.0 (1.1)	2.2 (.2)

APPENDIX (continued)

Tone Durations (sec/sec)	Incorrect VI	Responses				Time				Reinforcers			
		Hits	CRs	FAs	Misses	Hits	CRs	FAs	Misses	Hits	CRs	FAs	Misses
2/10	15-sec	117.0 (10.6)	111.2 (5.4)	52.4 (5.1)	46.4 (9.6)	1.4 (.1)	.9 (.1)	.8 (.1)	.5 (.1)	20.6 (.7)	17.8 (.7)	7.0 (.6)	4.6 (.7)
2/10	7.5-sec	91.0 (5.8)	97.8 (10.7)	51.4 (3.9)	43.8 (9.6)	1.1 (.1)	.9 (.1)	.6 (.1)	.4 (.1)	18.2 (.7)	15.2 (.9)	9.6 (.8)	7.0 (.8)
2/10	5-sec	63.6 (5.4)	102.4 (12.8)	75.6 (8.1)	66.8 (12.1)	.5 (.1)	.9 (.1)	.7 (.1)	.5 (.1)	12.4 (1.0)	13.8 (1.2)	12.6 (.9)	11.2 (1.5)
2/10	7.5-sec	109.2 (6.5)	96.2 (10.2)	93.8 (11.0)	57.2 (10.9)	1.0 (.1)	.7 (.1)	.9 (.1)	.5 (.1)	17.0 (.8)	13.2 (.9)	11.0 (1.1)	8.8 (.9)
2/10	15-sec	114.2 (9.5)	96.4 (7.5)	57.2 (6.5)	76.4 (9.6)	1.2 (.1)	.9 (.1)	.7 (.1)	.9 (.1)	19.8 (1.2)	15.6 (1.1)	7.6 (.4)	7.0 (.8)
2/10	30-sec	119.0 (5.3)	145.8 (5.3)	51.2 (11.2)	81.8 (12.0)	1.1 (.1)	1.2 (.1)	.7 (.1)	.9 (.1)	19.4 (.7)	22.0 (.9)	3.8 (1.2)	4.8 (.7)
2/10	60-sec	145.2 (14.8)	196.8 (17.6)	59.4 (8.5)	79.4 (8.7)	1.2 (.2)	1.3 (.1)	.9 (.2)	1.1 (.3)	21.0 (2.0)	23.8 (1.9)	2.4 (.2)	2.8 (.7)
3/9	60-sec	171.4 (15.2)	138.0 (21.8)	79.4 (16.0)	119.8 (18.6)	1.3 (.2)	1.0 (.2)	1.2 (.3)	1.3 (.2)	25.6 (2.6)	19.2 (2.9)	1.8 (.3)	3.4 (.7)
3/9	30-sec	140.2 (14.6)	139.4 (11.6)	117.4 (10.1)	68.6 (15.0)	1.3 (.1)	1.0 (.1)	1.5 (.1)	.7 (.2)	23.4 (1.3)	18.2 (1.3)	5.6 (.4)	2.8 (.4)
3/9	15-sec	78.6 (8.7)	66.2 (2.2)	58.0 (3.1)	56.2 (6.1)	1.4 (.2)	.9 (.1)	1.1 (.1)	1.1 (.1)	19.4 (1.4)	15.2 (.7)	8.8 (.8)	6.6 (1.3)
3/9	30-sec	129.0 (5.5)	95.6 (10.1)	98.6 (14.0)	68.2 (9.2)	1.5 (.1)	.9 (.1)	1.6 (.2)	.9 (.1)	22.8 (1.3)	16.8 (1.2)	6.6 (.6)	3.8 (.8)
3/9	60-sec	148.6 (8.8)	130.2 (10.4)	125.6 (11.0)	73.8 (6.2)	1.4 (.1)	1.1 (.1)	1.8 (.2)	.9 (.1)	24.8 (.8)	21.8 (.9)	2.2 (.3)	1.2 (.3)
3/9	120-sec	135.2 (11.9)	179.2 (14.3)	75.4 (9.4)	81.0 (9.8)	1.4 (.2)	1.4 (.1)	1.1 (.2)	.8 (.1)	21.2 (1.3)	24.8 (1.0)	2.4 (.4)	1.6 (.5)
<i>Subject 3—Data Until First Changeover</i>													
2/10	extinction	149.6 (13.0)	157.0 (13.2)	20.2 (3.0)	22.8 (4.4)	1.3 (.1)	1.4 (.1)	.3 (.1)	.4 (.1)				
2/10	120-sec	130.6 (10.9)	181.0 (10.1)	6.4 (2.8)	22.4 (9.4)	1.4 (.1)	1.5 (.1)	.2 (.1)	.2 (.1)	20.6 (2.1)	21.4 (1.9)	0.0 (0.0)	.2 (.2)
2/10	60-sec	105.2 (19.5)	135.2 (10.3)	29.2 (14.3)	53.4 (11.2)	1.2 (.2)	1.1 (.1)	.6 (.2)	.6 (.2)	15.4 (1.4)	20.0 (1.6)	1.0 (.4)	2.0 (.6)
2/10	30-sec	137.4 (13.6)	127.2 (10.0)	46.4 (9.3)	14.0 (7.1)	1.4 (.1)	1.0 (.1)	.6 (.1)	.1 (.1)	20.4 (2.0)	14.6 (.8)	2.4 (.9)	.8 (.2)
2/10	15-sec	110.0 (11.1)	98.6 (2.9)	50.0 (5.0)	37.0 (12.3)	1.3 (.1)	.9 (.1)	.7 (.1)	.4 (.2)	18.8 (1.0)	15.0 (.5)	6.4 (.4)	2.6 (.8)
2/10	7.5-sec	90.4 (6.2)	95.6 (11.0)	45.4 (2.8)	37.0 (8.4)	1.0 (.1)	.9 (.1)	.6 (.1)	.4 (.1)	18.0 (.8)	14.4 (.9)	8.6 (.6)	5.8 (.9)
2/10	5-sec	63.6 (5.4)	95.6 (11.4)	74.6 (8.7)	66.0 (12.0)	.5 (.1)	.9 (.2)	.7 (.1)	.5 (.1)	12.4 (1.0)	12.6 (1.2)	12.4 (1.0)	11.0 (1.4)
2/10	7.5-sec	109.2 (6.5)	87.8 (9.8)	86.2 (10.4)	49.4 (12.4)	1.0 (.1)	.7 (.1)	.8 (.1)	.4 (.1)	17.0 (.8)	11.2 (1.1)	10.4 (1.2)	7.0 (1.3)
2/10	15-sec	96.0 (10.7)	82.8 (5.3)	55.0 (5.9)	68.4 (9.5)	1.0 (.1)	.8 (.1)	.6 (.1)	.9 (.1)	15.6 (1.4)	12.4 (.8)	7.4 (.5)	5.6 (1.0)
2/10	30-sec	94.4 (4.2)	125.6 (8.2)	38.8 (6.8)	75.0 (9.8)	1.0 (.0)	1.1 (.1)	.6 (.1)	.9 (.1)	13.8 (.9)	17.2 (1.2)	2.8 (.9)	4.4 (.5)
2/10	60-sec	116.8 (10.9)	170.6 (19.7)	43.2 (4.2)	62.2 (11.3)	1.1 (.2)	1.2 (.1)	.8 (.2)	.7 (.3)	15.6 (1.2)	18.8 (2.2)	1.8 (.5)	2.4 (.7)
3/9	60-sec	116.0 (11.9)	113.2 (20.0)	58.4 (10.6)	96.8 (19.3)	1.0 (.1)	.8 (.2)	.9 (.2)	1.1 (.2)	15.2 (2.0)	14.4 (2.2)	.8 (.3)	2.2 (.3)
3/9	30-sec	115.8 (11.4)	109.4 (11.0)	82.6 (9.3)	61.6 (14.1)	1.1 (.2)	.9 (.1)	1.1 (.1)	.7 (.2)	18.0 (1.7)	11.6 (1.2)	4.8 (.5)	2.4 (.5)
3/9	15-sec	64.2 (6.7)	59.4 (1.7)	51.0 (1.7)	51.4 (5.3)	1.2 (.2)	.8 (.1)	1.0 (.1)	1.1 (.1)	15.0 (.8)	13.0 (.6)	7.6 (.7)	5.8 (1.3)
3/9	30-sec	107.6 (6.2)	72.4 (8.5)	77.2 (16.5)	62.8 (8.9)	1.4 (.1)	.7 (.1)	.8 (.3)	.8 (.1)	17.2 (1.5)	11.2 (.7)	4.8 (.7)	2.8 (.7)
3/9	60-sec	113.2 (10.0)	92.0 (8.5)	101.2 (13.0)	63.4 (6.3)	1.2 (.1)	.8 (.1)	1.5 (.2)	.8 (.1)	17.0 (1.6)	13.0 (1.0)	1.8 (.3)	.8 (.3)
3/9	120-sec	109.4 (13.0)	155.4 (15.4)	56.4 (9.4)	72.2 (8.9)	1.2 (.2)	1.2 (.1)	.9 (.1)	.8 (.1)	16.0 (2.0)	19.4 (.8)	1.2 (.5)	1.4 (.5)