*THE INTERACTION OF STIMULUS AND REINFORCER
CONTROL IN COMPLEX TEMPORAL DISCRIMINATION*

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Six pigeons were trained in a discrete-trials signal-detection procedure to discriminate between a fixed-duration stimulus (5 s or 20 s) and a set of variable durations ranging from 2.5 s to 57.5 s in steps of 5 s. For each fixed-duration stimulus, the ratio of reinforcer frequencies contingent upon reporting the fixed versus the variable stimulus was systematically manipulated. Detection performance was well controlled by both the stimulus value and the reinforcer ratio. Both the discriminability between the fixed duration and the set of variable durations, and the discriminability between the fixed duration and each of the variable durations, were independent of the reinforcer-frequency ratio when discriminability was measured as $\log d$. The sensitivity of response bias to reinforcement-ratio changes was independent of the value of the fixed duration, but was not independent of the discriminability of the variable durations from the fixed durations. Under current models, discriminability measures in complex temporal discrimination may be independent of biasing manipulations, but bias measures are not independent of stimulus values.

Key words: signal detection, complex temporal control, discriminability, bias, sensitivity to reinforcement, key peck, pigeons

Behavior in psychophysical tasks is determined jointly by stimulus differences and by differential reinforcement. Signal detection models (e.g., Green & Swets, 1974) have been developed to determine whether measures of performance can be found that vary as a function of stimulus differences independently of differential reinforcement, and whether other measures can be found that vary as a function of differential reinforcement independently of stimulus differences. However, in a simple two-stimulus discrimination task, McCarthy and Davison (1984) demonstrated empirically that detection-theory measures of the effect of stimulus differences (i.e., d' , or discriminability) were not independent of measures of the effect of differential reinforcement (i.e., β_{obs} , or response bias). By contrast, similar measures defined by Davison and Tustin (1978) (namely, $\log d$ and $\log$ response bias; Equations 3 and 4, respectively) did have the required independence.

McCarthy and Davison (1986) tested the

independence of Davison and Tustin's (1978) measures in a complex multistimulus temporal discrimination task in which one stimulus was a single duration while the other was a class of 12 different durations, ranging from 2.5 s to 57.5 s. They found that changing the value of the single duration across conditions from 5 to 55 s (a stimulus manipulation assumed to affect only discriminability) produced correlated changes in the measure of response bias. Raslear (1983), in a temporal-discrimination study, likewise noted that response bias (measured by B'' , Grier, 1971) was related to the duration of the intervals to be bisected.

In complex temporal discrimination tasks, then, the independence of stimulus discriminability measures and response bias measures defined by Davison and Tustin (1978) seems to be violated. However, McCarthy and Davison (1986) did not report any manipulation of the sort of nondiscriminative events that should influence response bias, so their experiment provided no information on the effect that differential reinforcement manipulations might have on discriminability measures. Thus, the present study was designed to determine whether, in the same complex temporal discrimination task as used by McCarthy and Davison, variations in differential reinforcement would affect the Davison-Tustin (1978) measure of discriminability.

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		RESPONSES	
		FD CHOICE	VD CHOICE
		(Left, C1-C8) (Right, C9-C18)	(Right, C1-C8) (Left, C9-C18)
S T I M U L I	FD X S	W	X
	VD 2.5 S	Y _i	Z _i
	VD 7.5 S		
	.		
	.		
	VD 57.5 S		

Fig. 1. The matrix of stimulus and response events in the temporal discrimination task. FD *x*-s denotes the fixed duration, and VD 2.5 s, VD 7.5 s, . . . , VD 57.5 s, the components of the variable-duration set. FD choice and VD choice denote the two response alternatives: Left key pecks were correct FD choices in Conditions 1 to 8, and right key pecks were correct FD choices in Conditions 9 to 18; right key pecks were correct VD_i choices in Conditions 1 to 8, and left key pecks were correct VD_i choices in Conditions 9 to 18. W, X, Y, and Z define the cells of the matrix.

Changes in response-bias measures that occur when stimuli are changed have minimal theoretical consequence in studies designed primarily to measure temporal control if a measure of accuracy is employed which is invariant with changes in bias (McCarthy & Davison, 1986). However, the dependent variable typically used in temporal-discrimination studies is the proportion of “long” (or “short”) responses (e.g., Church & Deluty, 1977; Raslear, 1983; Stubbs, 1976b). Clearly, the probability of a “long” (or “short”) response may be high following presentations of a “long” (or “short”) duration because of high accuracy and/or because the animals’ performance is biased toward reporting the “long” (or “short”) duration. Such a dependent variable, then, may not provide an estimate of the animals’ ability to discriminate between stimulus durations that is free of response bias. Hence, the measure of the control exerted by the stimuli may be inaccurate (Raslear, 1985). In contrast, if changes in biasing factors, such as differential reinforcement, affect the measure of discriminability defined by a model, the implications of such an effect for studies designed to measure temporal control are minimal if response bias was unchanging across stimulus differences or if the variables known to affect

response bias were held constant by the experimental procedure (the “controlled” reinforcement-ratio procedure as described by McCarthy & Davison, 1984, and as used by Stubbs, 1976a, 1976b). Most temporal discrimination studies have not controlled differential reinforcement experimentally, and hence the discriminability measures they used may have been affected by response-bias changes. Indeed, when response bias has been measured (Gibbon & Church, 1981; Raslear, 1983), it has been found to vary as a function of sensory-event values. Finally, any influence of response-bias operations on sensory measures, or of stimulus operations on response-bias measures, simply indicates that the model used to define such measures is incorrect. Within a model, the measurement of the effect of a defined manipulation must be independent of other, orthogonal, defined manipulations.

By systematically varying response bias, the present experiment sought to assess McCarthy and Davison’s (1986) suggestion that when multiple, rather than single, durations are used as the components of signaling stimuli in temporal-discrimination studies, known discriminability-free measures of response bias and bias-free measures of stimulus discriminability defined by Davison and Tustin (1978) are not independent of each other. The same discrete-trials procedure that was used by McCarthy and Davison was used here; that is, 6 pigeons were trained to discriminate one fixed-duration light from a set of 12 different light durations. In one procedure, the fixed duration was 5 s; in the second procedure it was 20 s. In both procedures, the variable-duration set comprised the same 12 intervals ranging from 2.5 s to 57.5 s, with an arithmetic mean of 30 s. Response bias was systematically manipulated in both procedures by varying the frequency with which correct fixed-duration and variable-duration choices produced food reinforcers. The matrix of events in the present task is illustrated in Figure 1. The major question posed here was: Would discriminability measures remain the same for all relative reinforcer frequencies? In the context of the Davison-Tustin model, this question can be rephrased as: Would the sensitivity of response bias to reinforcer-ratio variations be the same in the presence of both the single- and multiple-duration stimuli?

Sensitivity to relative reinforcer frequency

in a discrete-trials paradigm is measured using the model suggested by Davison and Tustin (1978). This model has been successfully applied to many detection situations consisting of fixed, unitary, pairs of stimuli (e.g., McCarthy & Davison, 1981). According to this model, the exponent of the power function relating choice ratios in the presence of each of a pair of temporal stimuli to obtained reinforcer ratios is a measure of the sensitivity of discriminative performance to changes in relative reinforcer frequencies. Assuming that this model is also correct when the stimuli are classes, rather than unitary stimuli, then in logarithmic terms the Davison-Tustin model for performance in the presence of the fixed- and variable-duration stimuli used here can be expressed as follows:

On fixed-duration trials:

$$\log\left(\frac{B_w}{B_x}\right) = a_1 \log\left(\frac{R_w}{R_z}\right) + \log c + \log d, \quad (1)$$

and, on variable-duration trials (for simplicity we shall at this point collectively treat the 12 variable durations as one stimulus class):

$$\log\left(\frac{B_y}{B_z}\right) = a_2 \log\left(\frac{R_w}{R_z}\right) + \log c - \log d, \quad (2)$$

where B and R denote the numbers of responses emitted and the numbers of reinforcers obtained, respectively, and the subscripts refer to the cells of the matrix in Figure 1. The parameter $\log d$ acts as a measure of the discriminability of the temporal stimuli. As stimulus separation increases, more fixed-duration choices will be emitted when the fixed duration is presented, and more variable-duration choices will be emitted when the variable duration is presented. Since the numerators in both Equations 1 and 2 are fixed-duration choices, $\log d$ is positive in Equation 1 and negative in Equation 2. The ratio R_w/R_z is the ratio of obtained reinforcers for correct fixed-duration to variable-duration choices. The parameters a_1 and a_2 measure the relation between behavior and changes in a biaser. Specifically, they measure the sensitivity of choice ratios in the presence of each stimulus, respectively, to changes in the obtained reinfor-

er-frequency ratio. $\log c$ provides a measure of *inherent* bias, a preference which remains invariant across changes in the relative reinforcer distribution.

Equations 1 and 2 collectively provide an estimate of stimulus discriminability ($\log d$). When Equation 2 is subtracted from Equation 1, one obtains (with some rearrangement):

$$\log d = 0.5 \log\left(\frac{B_w B_z}{B_x B_y}\right) - 0.5(a_1 - a_2) \log\left(\frac{R_w}{R_z}\right). \quad (3)$$

It can be seen from Equation 3 that when $a_1 = a_2$, reinforcer sensitivity has no effect on the measure of discriminability, $\log d$. Under these conditions, then, discriminability will be independent of response biases produced by varying relative reinforcer frequencies. When we have employed unitary, fixed stimuli (e.g., different intensities of white light, McCarthy & Davison, 1979, 1984), or two different, but unitary, stimulus durations (McCarthy & Davison, 1980), we have typically found a_1 to equal a_2 , and a values that generally lie in the range 0.4 to 0.8. Under the same conditions, we have also shown that the value of a is independent of measures of stimulus discriminability (McCarthy & Davison, 1980).

Stubbs (1976a) trained pigeons, using a discrete-trials psychophysical procedure, to discriminate between two mutually exclusive classes of durations. Following presentations of any duration from a set of five "short" center-key durations (11, 12, 13, 14, and 15 s), responses on a red side key were intermittently reinforced. Following presentations of any duration from a set of five "long" center-key durations (16, 17, 18, 20, and 22 s), responses on a green side key were intermittently reinforced. Stubbs varied, across conditions, the relative rate at which reinforcers were produced by correct side-key choices. He reported that discriminability (measured by A' , Grier, 1971) remained constant, but response bias (measured by B'' , Grier, 1971) changed, as a function of changes in relative reinforcer rates.

Davison and Tustin (1978) reanalyzed Stubbs' (1976a) data according to Equations 1 and 2 and found that, for two of the three birds at least, the sensitivity of choice on "short"

trials to changes in relative reinforcer rates (a_1) was equal to the sensitivity of choice on "long" trials (a_2). Thus, within the Davison-Tustin model, discriminability was independent of the response bias produced by varying relative reinforcer rates when two mutually exclusive classes were employed, with each containing the same number of durations.

If, however, a_1 was assumed equal to a_2 , but in fact they were not equal, the effects on the discriminability measure are clearly specified by Equation 3. For example, in the present design, if in fact $a_1 > a_2$, $\log d$ would appear smaller when performance was biased toward reporting the variable-duration stimulus (a negative log-reinforcer ratio) than when it was biased toward reporting the fixed-duration stimulus (a positive log-reinforcer ratio). Conversely, if in fact $a_1 < a_2$, $\log d$ would appear higher when performance was biased toward reporting the variable-duration stimulus than when it was biased toward reporting the fixed-duration stimulus. But, if a_1 and a_2 are measured, then Equation 3 specifies a discriminability measure that is independent of both the biasing manipulations and the sensitivity of behavior to such manipulations.

The present experiment was designed specifically to investigate whether or not sensitivities of behavior to changes in reinforcer ratios (a_1 , a_2) would differ as a function of which stimulus (fixed or variable) was presented. McCarthy and Davison (1986) already demonstrated that bias measures were not independent of discriminability, and hence that the Davison-Tustin (1978) model with $a_1 = a_2$ could not accurately describe behavior in such a situation. The present experiment was designed to complement that of McCarthy and Davison, and to help determine the proper generalization of the Davison-Tustin model to the presentation of unequal-sized stimulus classes.

Because the present experiment used as one of the signaling stimuli a class of stimuli rather than a unitary stimulus, the experiment also provided stable-state generalization data (Blough, 1975; Church & Gibbon, 1982) under discriminative control of temporal stimuli. The present procedure differs from the usual steady-state generalization procedure in two ways: First, different explicit responses produced reinforcers in the presence of each stimulus class, rather than responding versus not

responding. Second, the procedure arranged different reinforcer rates for the two responses, rather than reinforcers for a defined response and extinction for the alternative response (but see Blough, 1975).

METHOD

Subjects

Six experimentally naive homing pigeons, numbered 181 to 186, served. They were maintained at $85\% \pm 15$ g of their free-feeding body weights by provision of supplementary mixed grain in their home cages after each experimental session. Water and grit were available in the home cages at all times.

Apparatus

The light-proof and sound-attenuated chamber was situated remote from a PDP 8E® computer running SUPERSKED® software that controlled all experimental events. Masking noise was provided by an exhaust fan. The chamber contained three response keys, 2 cm in diameter, 10 cm apart, and 24 cm above the grid floor. The center key, when operative, was transilluminated white, and the two outer keys, when operative, were transilluminated red. The luminance of the white center key was 5.01 cd/m². The two side keys, when illuminated, were operated by pecks exceeding about 0.1 N. No center-key pecks were required throughout the experiment. A food magazine was situated beneath the center key and 10 cm above the grid floor. The reinforcer was 3-s access to wheat, and during this time the key-lights were extinguished and the illuminated food magazine was raised. A houselight provided the only other source of illumination in the chamber.

Procedure

The birds initially received nine sessions of magazine training. Key pecking was auto-shaped on all keys, each illuminated white, red, and green, and then maintained on a variety of reinforcement schedules for 42 sessions. Following this, the main experimental procedure began, and in 18 experimental conditions each bird was trained to detect differences between stimulus durations. The sequence of procedures and conditions, and the

number of training sessions conducted in each, are shown in Table 1.

In all conditions of both experimental procedures, trials began with the simultaneous onset of the houselight and of the white center keylight for one of 13 durations. During this time, the two side keys were dark and inoperative. On one half of the trials, randomly determined, the center key was lit white, and the houselight came on, for a fixed duration (FD) of 5 s (Conditions 1 through 10) or 20 s (Conditions 11 through 18). On the other half of the trials, the duration of the white center keylight and houselight was one of 12 durations (designated VD_i), the average of which was 30 s. These 12 durations were taken from an arithmetic series of the form $a, a + d, a + 2d$, and so on, in which $a = d/2$. Specifically, the durations (i) in seconds were: 2.5, 7.5, 12.5, 17.5, 22.5, 27.5, 32.5, 37.5, 42.5, 47.5, 52.5, and 57.5. Each of the 12 durations comprising the variable-duration (VD) stimulus was presented with equal probability on VD trials in a random sequence without replacement.

At the end of the time interval signaled by the simultaneous presentation of the center keylight and the houselight, the center keylight and the houselight were extinguished and the two side keys were lit red. The simultaneous offset of the white center keylight and of the houselight, and the onset of the red side-keylights, were independent of the pigeons' behavior. Reinforcers were occasionally available for two kinds of responses: A left key peck following the fixed (5-s) center-key duration (designated L/FD 5), or a right key peck following one of the durations of the variable-duration stimulus set (R/VD_i), in Conditions 1 through 8. In Conditions 9 to 18, these contingencies were reversed. That is, right key pecks following the fixed duration and left key pecks following presentation of one of the components of the variable-duration stimulus were occasionally reinforced. Hereinafter, we shall refer to these two types of responses as correct FD choices and correct VD_i choices.

In all experimental conditions, a correct FD choice produced a reinforcer if a probability gate, sampled after each reinforcer, had arranged a reinforcer for that choice. Once set up, the reinforcer remained available for the selected choice (correct FD or correct VD) until it was delivered. This scheduling arrangement ensured that the relative frequencies of

Table 1

The sequence of experimental procedures and conditions, and the number of training sessions given in each. FD denotes the value of the fixed-duration stimulus in seconds. In all conditions, the components of the variable-duration stimulus were a set of 12 durations ranging from 2.5 s to 57.5 s, with an arithmetic mean of 30 s. $p(R/FD)$ denotes the probability with which a food reinforcer was delivered for a correct FD choice relative to that for a correct VD_i choice.

Procedure	Condition	FD	$p(R/FD)$	Sessions
A	1	5	.1	26
	2		.5	28
	3		.65	26
	4		.3	25
	5		.725	27
	6		.2	28
	7		.8	31
	8		.4	28
	9		.1	31
	10		.5	27
B	11	20	.5	30
	12		.725	25
	13		.2	22
	14		.65	22
	15		.3	20
	16		.8	25
	17		.1	26
	18		.4	24

reinforcers obtained from the side keys remained fixed at the arranged values (Stubbs, 1976a). In both procedures, the relative frequency of a food reinforcer for a correct FD x -s choice was varied from .1 to .8 across experimental conditions (Table 1). A correct response emitted when the reinforcer was arranged for the alternate choice was followed by a 3-s blackout of all chamber lights.

In Conditions 1 to 8 inclusive, right key pecks following the fixed duration, or left key pecks following one of the variable durations (i.e., R/FD 5 s or L/VD_i), resulted in a 3-s blackout. In Conditions 9 to 18, left key pecks following the fixed duration and right key pecks following one of the variable durations (i.e., L/FD x s and R/VD_i) resulted in a 3-s blackout. We shall subsequently refer to these two types of responses as incorrect FD choices and incorrect VD_i choices. During blackout, all chamber lights were extinguished and key pecks had no scheduled consequences. A new trial (simultaneous onset of the white center keylight and houselight) began after either food or blackout. Throughout the experiment, a

noncorrection procedure was used: The duration of the white center keylight and houselight on Trial n was independent of choice accuracy and stimulus duration on Trial $n - 1$.

Experimental sessions were conducted 7 days per week. The training sessions began in blackout and ended in blackout either when 100 trials had been completed or when 40 min had elapsed. The data collected were the numbers of FD and VD_i choices emitted and the numbers of food reinforcers produced by correct FD choices and by correct VD_i choices, following presentations of each of the 13 durations. Experimental conditions were changed only when all birds' performances had met two stability criteria. Following a minimum of nine training sessions, the median discriminability and response-bias values were calculated across successive blocks of three consecutive training sessions. Discriminability was calculated using Equation 3, assuming $a_1 = a_2$. Response bias was calculated using the formulation derived by adding Equations 1 and 2 (Davison & Tustin, 1978). With some rearrangement, this gives the following estimate of response bias, which is expected to be discriminability-free whether or not $a_1 = a_2$:

$$\log \text{ response bias} = 0.5 \log \left(\frac{B_w B_y}{B_x B_z} \right). \quad (4)$$

The criteria required no monotonic increasing or decreasing trends in either of these two measures. As a result, the minimum number of training sessions in each condition was 18. As conditions were not necessarily changed immediately when stability was reached, the number of training sessions conducted in each condition ranged from 20 to 31, with a mean of 26 averaged across all conditions. The mean number of trials per condition was thus 2,600.

RESULTS

The numbers of FD and VD_i choices emitted and the numbers of food reinforcers produced by correct FD and VD_i choices following presentation of each of the 13 durations are shown in the Appendix. Those are group data. That is, they were first summed over the

final seven sessions of each experimental condition for individual birds, and then averaged over all birds.

Collectively, the data presented in the Appendix show first that choice accuracy was higher when the fixed duration was 5 s (Conditions 1 through 10) than when it was 20 s (Conditions 11 through 18). For example, compare the data obtained in Condition 3 with those obtained in Condition 13, in both of which the relative frequency of a reinforcer for a correct FD choice was .65. In Condition 3, the FD was 5 s, 317 correct FD 5-s choices were emitted, 292 correct VD_i choices were emitted, 54 incorrect FD 5-s choices were emitted, and 36 incorrect VD_i choices were emitted (87% correct). In Condition 13, the FD was 20 s, 233 correct FD 20-s choices were emitted, 163 correct VD_i choices were emitted, 135 incorrect FD 20-s choices were emitted, and 65 incorrect VD_i choices were emitted (66% correct). A similar difference in accuracy between the two procedures can be seen by comparing other conditions with equivalent relative reinforcer frequencies (e.g., Conditions 1 and 16, 2 and 10, 4 and 14, and so on).

Second, these data also show accuracy changes across the range of VD_i stimuli within each condition. Specifically, in the FD 5-s procedure, at VD_i durations progressively longer than the fixed (5-s) duration, increasingly more VD_i than FD 5-s choices were emitted. In the FD 20-s procedure, however, more VD_i than FD 20-s choices were emitted at short and long VD_i durations. But, following presentations of VD 17.5 s to VD 27.5 s, either more FD 20-s than VD_i choices were emitted or approximately equal numbers of FD 20-s and VD_i choices were emitted, depending upon the reinforcer probability.

Finally, these data show that, across all conditions in both procedures, more responses were emitted on, and more food reinforcers were obtained from, the choice alternative correlated with the higher relative frequency of reinforcement. For example, in Condition 1, the frequency of a reinforcer for a correct VD_i choice relative to that for a correct FD 5-s choice was .9. Correspondingly, a total of 531 VD_i choices was emitted compared with 152 FD 5-s choices, and a total of 272 reinforcers was obtained for correct VD_i choices compared with only 30 for correct FD 5-s choices.

Fig. 2. Individual subjects' data from the FD 5-s procedure: The vertical axis shows proportions of FD 5-s choices (left key pecks) in each of the 13 durations as functions of the logarithm of stimulus duration (horizontal axis) and the relative frequency of reinforcers, $p(R/FD)$, shown on the third axis.

Stable-State Generalization Data

Figure 2 shows for each bird the proportion of FD 5-s choices (left key pecks) in Conditions 1 to 8, and Figure 4 shows for each bird the proportion of FD 20-s (right key pecks) in Conditions 11 to 18, as a function of both the reinforcer-frequency ratio (z axis) and the (logarithmic) durations (x axis). The corresponding group data are shown in Figures 3 and 5, respectively. One stable-state generalization gradient was obtained for each arranged relative reinforcer frequency for correct FD choices.

Consider first the data obtained when the fixed duration was 5 s (Figures 2 and 3). Although the highest proportion of FD 5-s choices was usually emitted following presentation of the FD 5-s stimulus, in some conditions it occurred at the shortest VD_i stimulus, that is, VD_2 2.5 s. As the duration of the VD_i stimulus was lengthened relative to the FD 5-s stimulus, proportionally more VD_i than FD 5-s choices were emitted. Likewise, when the fixed duration was 20 s (Figures 4 and 5), the peak of the gradient usually occurred at or close to the

FD 20-s stimulus value. Figures 2 to 5 show that the gradients became lower and flatter as the relative reinforcer frequency was decreased for both the FD 5-s and the FD 20-s performances.

Fig. 3. Group data from the FD 5-s procedure, showing the proportion of FD 5-s choices (left key pecks) in each of the 13 durations as functions of the logarithm of stimulus duration and the relative frequency of reinforcers, $p(R/FD)$.

Fig. 4. Individual subjects' data from the FD 20-s procedure, showing the proportion of FD 20-s choices (right key pecks) in each of the 13 durations as functions of the logarithm of stimulus duration and the relative frequency of reinforcers, $p(R/FD)$.

In Conditions 9 and 10 of the FD 5-s procedure, correct FD 5-s responses were right-key responses, rather than left-key responses as in Conditions 1 to 8, and the relative frequency of a reinforcer for a correct FD 5-s choice was .1 and .5, respectively. Figure 6 shows the data obtained from these two con-

ditions, together with the data from the same relative reinforcer frequency values in Conditions 1 to 8. The gradients obtained in these two key-reversal conditions were very similar to the data from the equivalent original conditions (Conditions 1 and 2).

Fig. 5. Group data from the FD 20-s procedure, showing the proportion of FD 20-s choices (right key pecks) in each of the 13 durations as functions of the logarithm of stimulus duration and the relative frequency of reinforcers, $p(R/FD)$.

Fig. 6. Data summarizing the effects of reversing the relations between key location and discriminative contingencies. The proportion of FD 5-s choices (left key pecks in Conditions 1 and 2, right key pecks in Conditions 9 and 10) in each of the 13 durations is shown as functions of the logarithm of stimulus duration and the relative frequency of reinforcers, $p(R/FD)$.

Influence of Variation in Relative Reinforcer Frequency

The parameters a_1 and a_2 in Equations 1 and 2 measure the sensitivity of response allocation following presentations of the temporal stimuli to changes in relative reinforcer rates. Accordingly, Equations 1 and 2 were fit to the present data to obtain these choice-sensitivity measures. However, because of the multiple nature of the temporal stimuli used in the present experiment, Equation 2 can be applied to the data in two different (but related) ways. The 12 components of the VD stimulus set can be collectively treated as one stimulus. Thus, behavior in the presence of all components can be summed (we shall refer to this as overall VD performance), and Equation 2 can be fitted to the summed data to provide a measure (a_2) of the sensitivity of overall VD performance to changes in relative reinforcer rates. Alternatively, each of the 12 VD_i components can be analyzed as separate (discrete) durations, and Equation 2 can be fitted to behavior in the presence of each duration (we shall refer to this as VD_i performance). In this case, a_2 provides a measure of the sensitivity of VD_i performance to changes in relative reinforcer rates. Both types of analysis were carried out here. The first illustrates the behavioral result of the detection of a unitary stimulus from a class of stimuli when the class cannot be further decomposed into subclasses. An example might be the discrimination of a pure tone from general laboratory noise. The second analysis shows how this overall performance results from differing performances in each stimulus subclass.

Overall VD performance: FD 5-s procedure. Consider first the data obtained in Conditions 1 to 8 of the FD 5-s procedure. In these conditions, left key pecks were correct FD 5-s choices and right key pecks were correct VD_i choices. The relative frequency with which correct choices produced food was varied across eight experimental conditions (Table 1). Figure 7 (left panel) shows the logarithm of the ratio of the number of FD 5-s (left) to overall VD (right) choices on FD 5-s trials (i.e., $\log(B_w/B_x)$, squares) and on the sum of all VD_i trials (i.e., $\log(\Sigma B_y/\Sigma B_z)$, triangles) as a function of the logarithm of the obtained FD/VD reinforcer ratio (i.e., $\log(R_w/\Sigma R_z)$). The data plotted in Figure 7 are sums over the final seven sessions of each experimental condition

for Birds 182 and 186 (these 2 subjects were selected at random) and also for the group. These plots correspond to Equations 1 and 2. The data for overall VD performance were obtained by summing the number of FD 5-s (left) choices (ΣB_y) and VD_i (right) choices (ΣB_z) emitted following presentations of each of the 12 VD_i stimuli (see Appendix). Similarly, the total number of reinforcers produced by correct VD_i choices was the sum of all right-key reinforcers obtained after each VD_i stimulus (ΣR_z). Straight lines were fitted using the method of least squares to the mean data for each of the eight experimental conditions. The best-fitting straight lines, together with their equations and the standard deviations of the parameters, are shown in Figure 7. The parameters were estimated quite precisely as shown by the reasonably small standard deviations.

The slopes measure the sensitivity of choice in each (FD 5-s or overall VD) stimulus to changes in the relative frequency of reinforcers produced by correct choices. For the group data, the slope for FD 5-s performance (a_1 in Equation 1) was 0.92 ($SD = 0.07$), and that for overall VD performance (a_2 in Equation 2) was 0.18 ($SD = 0.04$). Table 2 shows these slope estimates for all birds. The results shown in Table 2 were obtained when Equations 1 and 2 were fitted (as above) to the data summed over the last seven sessions of each of the eight conditions for each of the 6 birds. As Table 2 shows, for all 6 birds, the sensitivity of choice on FD 5-s trials to changes in relative reinforcer frequency was higher than the sensitivity of choice on the sum of all VD_i trials (i.e., $a_1 > a_2$, Equations 1 and 2).

The intercepts of the relations displayed in Figure 7 and Table 2 are measures of $\log c$ (inherent bias) $\pm \log d$ (discriminability) when the independent variable, $\log(R_w/R_z)$, is zero. Thus, one half the sum of the intercepts of Equations 1 and 2 provides a measure of inherent bias ($\log c$), and one half the difference between the intercepts of Equations 1 and 2 provides a measure of discriminability ($\log d$), when $\log(R_w/R_z) = 0$. As the group data in Figure 7 show, discriminability between the FD 5-s stimulus and the set of VD_i stimuli was 0.77 (range, 0.67 to 0.92; Table 2). Inherent bias was -0.08 for the group (Figure 7), and ranged from -0.24 to 0.05 , as shown in Table 2.

Overall VD performance: FD 5-s procedure:

key reversal. Consider now the data obtained from Conditions 9 and 10. In these two conditions, a left-right key reversal was arranged: Left key pecks were correct following VD_i presentations, and right key pecks were correct following FD 5-s presentations. The relative frequency of a reinforcer for a correct FD 5-s (right-key) choice was either .1 (Condition 9) or .5 (Condition 10). The results of the analysis according to Equations 1 and 2 are shown for individual birds in Table 2.

Table 2 shows point estimates of the FD 5-s and overall VD sensitivities for individual birds. A Sign test (Siegel, 1956) showed that, for both FD 5-s and overall VD performance, these sensitivity estimates were not significantly different from those obtained from the regression fits to the data obtained in Conditions 1 to 8 ($p > .05$). The average FD 5-s sensitivities were 0.99 and 0.99 for Conditions 1 to 8 and Conditions 9 to 10, respectively. The average overall VD sensitivities were 0.18 and 0.25 for Conditions 1 to 8 and Conditions 9 to 10, respectively.

Table 2 shows point estimates of the intercepts for individual birds. A Sign test showed that, for both FD 5-s and overall VD performance, these intercepts were not significantly different from those obtained in Conditions 1 to 8 ($p > .05$). These results indicate that there was little inherent bias (i.e., $\log c$ in Equations 1 and 2 was zero), although individual subjects did show inherent biases to one or the other choice key. The reversals also show that the results obtained were independent of which of the two side-key responses provided reinforcers for the FD or the VD choices.

Overall VD performance: FD 20-s procedure. In Conditions 11 to 18, the fixed duration was 20 s. Right key pecks were correct FD 20-s choices and left key pecks were correct VD_i choices. The relative frequency with which correct FD 20-s choices produced food was varied (as in Conditions 1 to 8 of the FD 5-s procedure) from .1 to .8 across eight experi-

Table 2

Results obtained, shown for individual Birds 181-186, when Equations 1 and 2 were fitted to the mean data for each bird in Conditions 1 to 8 (FD 5-s procedure) and Conditions 11 to 18 (FD 20-s procedure), using least-squares linear regression. The slopes measure the sensitivities (a_1 and a_2) of the FD/VD choice ratio to changes in the obtained FD/VD reinforcer frequency ratio. The intercepts are a combination of inherent bias ($\log c$) and stimulus discriminability ($\log d$). The standard deviations (SD) of the parameter estimates are shown in parentheses. Eight data points were used in each regression analysis. Also shown in the right column are point estimates of the slopes and intercepts of Equations 1 and 2 for Conditions 9 and 10 of the FD 5-s procedure.

Bird	Slope (SD)	Intercept (SD)	Slope	Intercept
FD 5-s Procedure				
	Conditions 1 through 8		Conditions 9 and 10	
	Equation 1 (FD 5-s performance)			
181	0.75 (0.08)	0.53 (0.04)	1.24	0.88
182	0.93 (0.14)	0.75 (0.07)	0.83	0.68
183	0.89 (0.08)	0.86 (0.04)	1.03	0.91
184	1.01 (0.15)	0.50 (0.08)	1.04	0.71
185	1.24 (0.10)	0.80 (0.05)	1.07	0.92
186	1.09 (0.14)	0.89 (0.08)	0.71	0.63
	Equation 2 (overall VD performance)			
181	0.35 (0.09)	-0.81 (0.05)	0.61	-0.64
182	0.02 (0.10)	-0.89 (0.05)	0.03	-0.78
183	0.15 (0.07)	-0.97 (0.04)	0.04	-0.64
184	0.21 (0.18)	-0.97 (0.09)	0.42	-0.91
185	0.08 (0.07)	-0.78 (0.03)	0.03	-0.88
186	0.29 (0.06)	-0.80 (0.03)	0.34	-0.53
FD 20-s Procedure				
	Conditions 11 to 18			
	Equation 1 (FD 20-s performance)			
181	0.88 (0.08)	0.54 (0.04)		
182	0.90 (0.09)	0.37 (0.04)		
183	0.66 (0.07)	0.22 (0.03)		
184	0.84 (0.08)	0.59 (0.04)		
185	0.77 (0.10)	0.27 (0.05)		
186	0.85 (0.09)	0.42 (0.05)		
	Equation 2 (overall VD performance)			
181	0.52 (0.05)	-0.28 (0.03)		
182	0.36 (0.08)	-0.20 (0.04)		
183	0.54 (0.10)	-0.16 (0.05)		
184	0.46 (0.06)	-0.38 (0.03)		
185	0.52 (0.05)	-0.27 (0.02)		
186	0.51 (0.03)	-0.16 (0.02)		

Fig. 7. The logarithm of the ratio of the number of FD x-s choices to overall VD choices on both FD trials (open squares) and on the sum of all VD_i trials (open triangles) as a function of the logarithm of the obtained FD/VD reinforcer ratio. The left panel shows the data obtained in the FD 5-s procedure, and the right panel shows the data obtained in the FD 20-s procedure. These data are averaged over the final seven sessions of each experimental condition for Birds 182 and 186, and for the group data. The best-fitting straight lines by the method of least squares are shown for each stimulus (FD and VD) in each procedure, together with their equations and the standard deviations of the parameters (in parentheses).

Table 3

Results obtained when Equation 1 was fitted to FD performance and Equation 2 was fitted separately to performance occasioned by each of the VD_i stimuli, for the data averaged over subjects in both the FD 5-s procedure and the FD 20-s procedure. Least-squares linear regression analyses were used to obtain the slopes (a), which measure the sensitivity of the FD/ VD_i choice ratio in the presence of each stimulus to changes in the relative reinforcer frequency ratio. The intercepts (I) are a combined measure of inherent bias and discriminability ($\log c \pm \log d$). The standard deviations (SD) of the parameter estimates are shown in parentheses. All durations are in seconds.

Equation	Stimulus	a (SD)	I (SD)
FD 5-s Procedure			
1	FD 5	0.92 (0.07)	0.70 (0.02)
2	VD 2.5	0.71 (0.15)	0.55 (0.08)
	VD 7.5	0.32 (0.10)	-0.37 (0.05)
	VD 12.5	0.16 (0.09)	-0.82 (0.05)
	VD 17.5	0.21 (0.15)	-1.13 (0.08)
	VD 22.5	0.00 (0.16)	-1.39 (0.08)
	VD 27.5	0.00 (0.21)	-1.49 (0.11)
	VD 32.5	0.04 (0.21)	-1.56 (0.11)
	VD 37.5	0.00 (0.34)	-1.68 (0.18)
	VD 42.5	0.00 (0.34)	-1.76 (0.17)
	VD 47.5	-0.03 (0.21)	-1.61 (0.10)
	VD 52.5	-0.12 (0.16)	-1.71 (0.08)
	VD 57.5	-0.03 (0.29)	-1.73 (0.14)
FD 20-s Procedure			
1	FD 20	0.80 (0.05)	0.39 (0.03)
2	VD 2.5	0.14 (0.11)	-0.39 (0.06)
	VD 7.5	0.33 (0.06)	0.06 (0.03)
	VD 12.5	0.65 (0.06)	0.24 (0.03)
	VD 17.5	0.75 (0.08)	0.39 (0.04)
	VD 22.5	0.83 (0.06)	0.31 (0.03)
	VD 27.5	0.70 (0.05)	-0.004 (0.03)
	VD 32.5	0.65 (0.11)	-0.36 (0.05)
	VD 37.5	0.80 (0.06)	-0.53 (0.03)
	VD 42.5	0.74 (0.12)	-0.71 (0.06)
	VD 47.5	0.67 (0.07)	-0.79 (0.04)
	VD 52.5	0.50 (0.09)	-0.77 (0.04)
	VD 57.5	0.45 (0.10)	-0.88 (0.05)

mental conditions. Figure 7 (right panel) shows the analysis of these data according to Equations 1 and 2 for Birds 182 and 186, and for the group. Here, the logarithm of the ratio of the number of FD 20-s to the sum of VD_i choices on both FD 20-s and overall VD trials is shown as a function of the logarithm of the obtained FD/ VD reinforcer ratio. Straight lines were fitted, using the method of least squares, to the data averaged over the last seven sessions of each of the eight conditions. The best-fitting straight lines, together with their equations and the standard deviations of the parameters, are shown in the figure. The pa-

rameters were estimated quite precisely as shown by the small standard deviations.

Table 2 shows the slope estimates for individual birds. Consistent with the results of the FD 5-s procedure (also shown in Figure 7), the influence of relative reinforcer frequency on choice was greater on FD 20-s trials than it was on VD_i trials for all birds (i.e., $a_1 > a_2$, Equations 1 and 2).

The sensitivity values obtained in the FD 20-s procedure were compared with those obtained in the FD 5-s procedure (Conditions 1 to 8 only) using Wilcoxon matched-pairs signed-ranks tests (Siegel, 1956). The results showed that there was no significant difference ($p > .05$) between the sensitivity of choice on FD 5-s trials ($a = 0.92$; Figure 7) and the sensitivity of choice on FD 20-s trials ($a = 0.80$; Figure 7). For all 6 birds, however, sensitivity of choice on the sum of all VD_i trials was higher when the FD was 20 s than when the FD was 5 s.

Estimates of discriminability between FD 20 s and the set of VD_i stimuli (one half the difference between the intercepts of Equations 1 and 2 when $\log(R_w/R_z) = 0$) were 0.32 for the group (Figure 7), and ranged from 0.19 (Bird 183) to 0.49 (Bird 184), as shown in Table 2. For all birds, discriminability was lower when the fixed duration was 20 s than when it was 5 s. Estimates of inherent bias (one half the sum of the intercepts of Equations 1 and 2 when $\log(R_w/R_z) = 0$) were 0.08 for the group (Figure 7), and ranged from 0 (Bird 185) to 0.13 (Birds 181 and 186). A Sign test showed that these inherent biases did not differ significantly ($p > .05$) from those obtained in the FD 5-s procedure.

Summary. To summarize to this point, Figure 7 and Table 2 show that choice was differentially sensitive to changes in relative reinforcer frequency in the presence of either the FD 5-s or the FD 20-s stimulus, and in the sum of all VD_i stimuli. In particular, changes in the relative frequency of reinforcers for correct choices influenced performance more when the stimulus duration was fixed at 5 s or 20 s than when it was a class of variable durations. Further, choice sensitivity on variable-duration trials was significantly higher ($p < .05$) when the fixed duration was 20 s than when it was 5 s. However, the results presented in Figure 7 and Table 2 were obtained when overall VD performance was analyzed. That

Fig. 8. The logarithm of the ratio of the number of FD to VD_i choices on both FD trials (squares) and on each of five VD_i trials (VD 2.5 s, upright triangles; VD 12.5 s, plus signs; VD 22.5 s, diamonds; VD 32.5 s, crosses; and VD 57.5 s, inverted triangles) as a function of the obtained FD/VD reinforcer ratio. The left panel shows data obtained in the FD 5-s procedure, and the right panel shows data obtained in the FD 20-s procedure. These data are averaged over the final seven sessions of each experimental condition for the group. The best-fitting straight lines by the method of least squares are shown for each stimulus (FD and VD_i) in each procedure, together with their slopes in parentheses. See text for further explanation.

is, performance in the presence of each VD_i stimulus was summed over all VD_i trials. But, as noted above, the 12 components of the VD set can be treated as 12 separate (discrete) stimuli. The following section analyzes choice in the presence of each of the 12 VD_i components.

Performance following each VD_i: FD 5-s procedure. Table 3 shows the mean results averaged over subjects obtained when Equation 2 was fitted to performance in each VD_i in Conditions 1 to 8 of the FD 5-s procedure. The dependent variable here was the logarithm of the ratio of the number of FD 5-s to VD_i choices on each VD_i trial, that is, $\log(B_{yi}/B_{zi})$. Figure 8 shows these fits for a sample of VD_i stimuli—VD 2.5 s, VD 12.5 s, VD 22.5 s, VD 32.5 s, and VD 57.5 s. For comparison, the results obtained when Equation 1 was fitted to the FD 5-s performance of the group (Figure 7 and Table 2) are again shown in both Figure 8 and Table 3. To aid clarity, the data from Conditions 9 and 10 are not shown in Figure 8. As Figure 6 and Table 2 clearly showed, in every major respect the data obtained from these two key-reversal conditions were consistent with those obtained from Conditions 1 to 8.

Least-squares linear regression analyses were used to obtain the equations of the best-fitting straight lines. The slopes (a_2 , Equation

2) of these regressions are measures of the sensitivity of choice following presentations of each of the 12 variable durations to changes in the relative frequency of reinforcers for correct choices. As the variable duration increased from 2.5 s to 57.5 s, reinforcer sensitivity decreased from 0.71 to -0.03 (Table 3). In other words, performance following the presentation of VD_i stimuli closer in duration to the FD 5-s stimulus was more sensitive to changes in relative reinforcer frequency than was performance in the presence of stimuli much longer in duration than the FD 5-s stimulus. Measures of discriminability between the FD 5-s stimulus and each of the VD_i stimuli will be presented in the *Stimulus Discriminability* section below.

Performance following each VD_i: FD 20-s procedure. Table 3 and Figure 8 also show the results obtained when the fixed duration was increased to 20 s. First, Table 3 shows the results obtained when Equation 2 was fitted to performance in each VD_i for the group. As the duration of the VD_i stimuli increased from 2.5 s to 17.5 s, reinforcer sensitivity (a) increased monotonically from 0.14 to 0.75. Reinforcer sensitivity was highest at VD 22.5 s ($a = 0.83$). As the duration of the VD_i stimuli was further increased beyond 22.5 s to 57.5 s, reinforcer sensitivity decreased (nonmonotonically) to 0.45. Figure 8 illustrates these results

Fig. 9. Estimates of discriminability between the FD stimulus and each of the VD_i stimuli as a function of the VD_i duration. These estimates were obtained using Equation 3 and are averaged across individual birds and reinforcer-frequency ratios in each procedure. The vertical bars denote ± 1 standard deviation unit.

for the VD 2.5-s, VD 12.5-s, VD 22.5-s, VD 32.5-s, and VD 57.5-s stimuli.

Consistent with the results obtained in the FD 5-s procedure, then, performance in the FD 20-s procedure following the presentation of VD_i stimuli was more sensitive to changes in relative reinforcer frequency the closer the duration of the VD_i stimulus was to 20 s. Measures of discriminability between the FD 20-s stimulus and each of the VD_i stimuli are presented below.

Stimulus Discriminability

Equation 3 was used to obtain estimates of discriminability (Equation 3) between the FD x -s stimulus and each of the VD_i stimuli, taking into account the differential reinforcer sensitivities reported in the previous section. Figure 9 shows these discriminability values, averaged across individual birds and reinforcer-frequency ratios, as a function of the VD_i duration. The vertical bars denote ± 1 standard deviation unit.

When the fixed duration was 5 s, discriminability measures were lowest (average $\log d_i = 0.06$) when the variable duration was 2.5 s. As the variable duration was lengthened relative to the fixed duration, discriminability increased to a maximum ($\log d_i = 1.02$) at the longest VD_i stimulus, VD 57.5 s. When the fixed duration was 20 s, discriminability was minimal ($\log d_i = 0$) at VD 17.5 s. As the variable duration was shortened or lengthened (relative to 17.5 s), discriminability increased to 0.43 at VD 2.5 s and to 0.68 at VD 57.5 s.

DISCUSSION

In this experiment, pigeons discriminated a fixed-duration stimulus from a variable set of 12 stimulus durations under different relative frequencies of reinforcement for correct choices. In one procedure the fixed duration was 5 s and in the other it was 20 s. In both procedures, the same variable set of 12 durations was used, and the durations in this set ranged from 2.5 s to 57.5 s, with an arithmetic mean of 30 s.

The maintained generalization gradients (Figures 2 to 6) showed that the temporal stimuli exerted good control over choice. In particular, the peaks of the gradients generally occurred at, or close to, the fixed duration. Changing the relative frequency of reinforcers for correct choices had most effect on the heights of the gradients at, or close to, the FD stimulus. In both procedures, the height of the gradient at the FD value was maximal when most of the sessional reinforcers were produced by correct FD choices and minimal when most of the reinforcers were produced by correct VD choices. Figures 2 to 6 also show that there were differential effects of relative reinforcer frequency variation on performance in the presence of each of the VD_i stimuli. Specifically, when the fixed duration was 5 s, changing the relative frequency of reinforcers for correct choices appeared to have little or no effect on performance when the durations of the VD_i stimuli were longer than about 22.5 s. But performances occasioned by VD_i stimuli of durations similar to the FD 5-s stimulus were strongly affected. Similarly, when the fixed duration was 20 s, performances following stimuli close to 20 s were more strongly affected by changing relative reinforcer frequencies than were performances following stimuli distant from 20 s.

Apart from displaying the data in a simple theory-free manner, the data plotted as stable-state generalization gradients (Figures 2 to 6) highlight the way in which relative reinforcer frequency affects the sharpness of stimulus control. When reinforcers for FD choices were relatively infrequent, stable-state gradients were much less peaked over the stimulus dimension than when FD choices were frequently reinforced. A similar result from a stable-state generalization procedure with temporal stimuli was reported by Church and Gibbon (1982, Experiment 4). In their experiment, the two criterion responses were responding and not responding for 5 s, and while the former was reinforced with two different probabilities, the latter remained unreinforced. The parallel results in the conventional stimulus-control literature are those of Hearst, Koresko, and Poppen (1964) who reported a direct relation between the steepness of single-stimulus generalization gradients and the reinforcer rate provided by the training schedules. The differences between the present procedure and that of Hearst et al. are that their alternative response (that is, not responding) was not explicit, and that their alternative reinforcer rate was unmeasured and uncontrolled and was simply the extraneous reinforcer rate in the experimental situation. All three results point to the same conclusion: that reinforcer rates, as well as stimuli, affect conventional measures of stimulus control. It is the purpose of the present detection analysis to attempt to dissociate stimulus and reinforcer effects, and thus to provide mutually independent measures of each.

The effects of both the values of stimulus durations and relative reinforcer frequencies apparent in the stable-state generalization gradients were confirmed and clarified by a behavioral detection analysis (Figures 7 to 10; Davison & Tustin, 1978). Consider the discriminability of the FD stimulus from each of the components of the VD_i stimulus. When the fixed duration was 5 s, discriminability between FD 5 s and each of the VD_i stimuli was minimal at the shortest VD_i stimulus (VD 2.5 s). At longer VD_i stimuli, discriminability increased (Figure 9). When the fixed duration was 20 s, discriminability between FD 20 s and each of the VD_i stimuli was minimal at VD 17.5 s. At shorter or longer VD_i durations, discriminability increased (Figure 9).

Fig. 10. The sensitivity of choice to changes in relative reinforcer frequency (a_i) in the presence of FD (crosses), and in the presence of each VD_i stimulus (squares), as a function of stimulus duration (measured in seconds). These data were averaged across individual birds, and the vertical bars denote ± 1 standard deviation unit.

Consider now the influence of changing the relative frequency with which reinforcers were produced by correct choices. Such effects are captured by the parameter a_i in Equations 1 and 2. Specifically, a_i provides a measure of how sensitive the animals' performance is to changes in the relative frequency of reinforcement. Four important findings emerged. First, as shown in Figure 7 and Table 2, performance in the presence of both FD 5 s and FD 20 s was more sensitive to changes in relative reinforcer frequency than was overall VD performance. Further, this result was maintained when the contingencies were reversed (Conditions 9 and 10), and was not, therefore, concerned with inherent key preferences. Second, sensitivities to reinforcer frequency ratios in the presence of FD 5 s and FD 20 s were not significantly different ($a_i = 0.92$ and 0.80 , respectively). Third, overall VD performance was more sensitive when the fixed duration was 20 s than when it was 5 s ($a_i = 0.49$ and 0.18 , respectively). Fourth, when performance was analyzed separately in the presence of each

VD_i stimulus, systematically changing reinforcer sensitivities were found within the set of durations (Figure 8 and Table 3).

Figure 10 summarizes these latter sensitivity values. Here, the sensitivity of choice to changes in the relative reinforcer frequency ratio in the presence of the FD stimulus and in the presence of each of the VD_i stimuli is plotted as a function of stimulus duration (scaled in linear units). Figure 10 clearly shows changes in a_i as a function of stimulus duration that were ordinaly related to the levels of discriminability seen in Figure 9. Specifically, when the fixed duration was 5 s, the sensitivity of choice to changes in relative reinforcer frequency was highest at the shortest VD_i stimulus (VD 2.5 s)—that is, when the discriminability of the FD 5-s stimulus from the components of the VD stimulus was minimal (Figure 9). Moreover, as the duration of the VD_i stimulus was lengthened relative to the fixed 5-s duration (and hence, discriminability increased, Figure 9), reinforcer sensitivity (a_i) decreased. When the fixed duration was lengthened to 20 s, the sensitivity values were highest for those VD_i stimuli close in duration to the FD 20-s stimulus; that is, when discriminability was lowest (Figure 9). And, as the VD_i duration was lengthened or shortened relative to the fixed 20-s duration (and hence discriminability increased, Figure 9), reinforcer sensitivity decreased. Two previous findings when both stimuli were fixed, rather than variable, show that these changes in sensitivity to reinforcement cannot be ascribed simply to changing levels of discriminability between the FD stimuli and distant VD_i stimuli. First, McCarthy and Davison (1979) found high sensitivities to reinforcement at greater discriminability levels than those obtained here. Second, McCarthy and Davison (1980) found no change in sensitivity values between log d values of about 0.4 and about 1.5, again beyond the range of log d values obtained here (compare Figure 9).

The major finding obtained in the present experiment, then, was an ordinal relation between stimulus discriminability and the sensitivity of choice to changes in relative reinforcer frequency. To summarize: (a) sensitivity to reinforcement was maximal, or close to maximal, following presentation of the FD stimuli, and (b) performance occasioned by VD_i stimuli less discriminable from the FD

stimulus was more sensitive to relative reinforcer frequency variation than was performance occasioned by VD_i stimuli that were more discriminable from the FD stimulus. This finding supports the suggestion made by McCarthy and Davison (1986) that the effects of variations in relative reinforcer frequency interacted with stimulus values in the discrimination between classes of temporal stimuli. The Davison-Tustin (1978) model was applied here without assuming that $a_1 = a_2$ in Equations 1 and 2, and when used in this way the measure of discriminability so defined (Equation 3) is independent of bias. The model, however, remains incorrect in another way. Sensitivity to reinforcement was affected by discriminability as measured by Equation 3, rather than being independent of this measure as required by Equations 1 and 2.

McCarthy and Davison (1980) showed clearly that sensitivity to reinforcement between pairs of (unitary) temporal stimuli was independent of the discriminability of the stimuli. Comparing those results with the present results, we conclude that the model of detection proposed by Davison and Tustin (1978) is an inappropriate model for understanding the effects of differential reinforcement on detection performance when the discriminative stimulus signaling one contingency consists of a class of stimuli. The limit of generality of the bias measure defined by that model appears to be the procedure that uses a pair of unitary stimuli. Evidently, when one contingency is signaled by a class of stimuli, there are interactions between this class and the alternate discriminative stimulus, and perhaps even within the stimulus class, which are not fully described by the Davison-Tustin model (Equation 3). We are presently investigating these interactions in detail in the discrimination between classes of colors with a view to providing a wider data base for the development of adequate generalization of the Davison-Tustin model for such procedures. Only when an appropriate model has been developed may bias measures that are independent of stimulus values be available for such a procedure.

The present results place limits on the procedures that may be used to test Davison and Tustin's (1978) behavioral detection model, and hence on procedures in which the measures defined by Davison and Tustin may be

used with confidence. First, some researchers (e.g., White, 1985; White & McKenzie, 1982) have used a procedure in which discriminabilities are varied over trials within sessions by arranging a set of variable delays between stimulus presentation and the availability of choice responses. Measures of response bias may not be independent of discriminability in this procedure. In a similar type of procedure, Nevin, Jenkins, Whittaker, and Yarensky (1982, Experiment 2) used, within sessions, a tone versus a noise to signal two different overall reinforcer rates maintaining the detection between 2-s and 3-s temporal stimuli. They found that measures of discriminability increased with overall reinforcer rate. In contrast to this finding, McCarthy and Davison (1982) reported that discriminability was independent of overall reinforcer rate in a procedure in which overall reinforcer rate was varied across experimental conditions. Again, the Davison-Tustin model may not be applicable to the second-order conditional discrimination used by Nevin et al. Second, more conventional temporal discrimination studies have typically varied temporal stimuli within sessions in order to measure the point of indifference between a standard fixed stimulus and comparison stimuli which vary in some way across trials (e.g., Church, Getty, & Lerner, 1976; Church & Gibbon, 1982; Gibbon & Church, 1981). In such procedures, there are two sources of variability: an across-conditions variability in the standard stimuli, and a trial-to-trial variability in the comparison stimuli. The present research strongly suggests that if temporal stimuli are used in such procedures, the Davison-Tustin detection model is not an appropriate model with which to measure response bias independently of discriminability. Other data that we have collected point to the same conclusion when contingencies are signaled by different wavelengths rather than durations. Because more conventional signal-detection measures have serious problems in describing even the simpler procedure of detecting just two unitary classes (McCarthy & Davison, 1984), there are still no mutually independent measures of stimulus and reinforcer effects available for such complex discrimination tasks.

The data presented here place constraints on the ability of current research methods, using current models, to describe behavior under

the joint control of temporal stimuli and of reinforcers. The model offered by Davison and Tustin (1978) provides measures of discriminability which are independent of reinforcer effects over a range of procedures, and thus overcomes Gibbon's (1981) plaint that "in a sense, reinforcement corrupts the inferences we wish to draw about the underlying [time] scale" (p. 182). Rather, these data suggest that when the Davison-Tustin model (Equation 3) is used to analyze performance in multiple-stimulus procedures, stimuli corrupt the inferences that we can currently draw about reinforcer scaling.

In conclusion, the importance of the present results is that they have increased the generality of the measure of discriminability but have circumscribed the use of the measure of bias, both of which were suggested by Davison and Tustin (1978). In doing so, however, we believe that we have provided a useful data base upon which to attempt the development of a quantitative model of stimulus generalization and, more generally, of multiple stimulus control.

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APPENDIX

Group data summed over the final seven sessions of each experimental condition and averaged over the 6 subjects. The data rows labelled "FD" and "VD" are the numbers of fixed-duration and variable-duration choices, respectively. (In Conditions 1 to 8, FD choices are left key pecks and VD choices are right key pecks. In Conditions 9 to 18, FD choices are right key pecks, and VD choices are left key pecks.) The data rows labelled "R" are the numbers of food reinforcers produced by these choices. The data column labelled "FD" shows the data (FD and VD choices) obtained following presentations of the FD x-s stimulus. Thus, for example, in Condition 1, 123 FD 5-s choices were emitted following presentations of FD 5 s (i.e., $B_w = 123$, Figure 1), and 214 VD choices were emitted following presentations of FD 5 s (i.e., $B_x = 214$, Figure 1). The remaining 12 columns show the data (FD and VD choices) obtained following presentations of each of the 12 variable durations (VD). Thus, for example, in Condition 1, 10 FD 5-s choices were emitted following presentations of VD 2.5 s (i.e., $B_{y1} = 10$, Figure 1), and 18 VD choices were emitted following presentations of VD 2.5 s (i.e., $B_{x1} = 18$, Figure 1). The reinforcer numbers in the "FD" column are those obtained for correct FD x-s choices, and the remaining 12 are those produced by correct VD choices. $p(R/FD)$ denotes the frequency with which a food reinforcer was delivered for a correct FD x-s choice relative to that for a correct VD choice.

		Stimuli											
		Variable-duration set											
	FD	1	2	3	4	5	6	7	8	9	10	11	12
Condition 1 $p(R/FD) = .1$													
FD	123	10	6	3	2	1	1	1	1	1	1	1	1
VD	214	18	24	26	27	28	27	27	28	29	27	28	28
R	30	16	21	23	23	25	23	23	23	25	23	23	24
Condition 2 $p(R/FD) = .5$													
FD	287	24	9	5	2	1	1	1	1	1	0	1	1
VD	49	5	20	25	27	28	28	28	29	29	30	29	28
R	157	4	11	12	13	13	15	15	14	14	14	12	14

APPENDIX

Continued.

	Stimuli												
	Variable-duration set												
	FD	1	2	3	4	5	6	7	8	9	10	11	12
Condition 3 $p(R/FD) = .65$													
FD	317	26	12	6	3	1	1	1	1	1	1	0	1
VD	36	2	17	24	26	27	28	27	28	28	28	28	29
R	211	2	9	8	10	13	11	11	10	12	10	12	10
Condition 4 $p(R/FD) = .3$													
FD	246	20	8	3	2	1	0	0	0	0	1	1	0
VD	92	10	21	26	27	28	29	28	29	29	29	28	29
R	91	9	17	19	20	21	21	19	21	20	21	19	23
Condition 5 $p(R/FD) = .725$													
FD	326	25	9	3	1	1	1	0	0	0	0	0	0
VD	24	4	21	27	28	28	28	29	29	29	29	29	29
R	242	2	5	7	8	10	10	10	9	10	9	8	9
Condition 6 $p(R/FD) = .2$													
FD	188	17	4	3	1	3	2	1	1	2	1	1	1
VD	157	12	26	26	28	27	28	29	28	28	28	28	28
R	65	11	20	20	20	19	21	21	20	20	21	20	20
Condition 7 $p(R/FD) = .8$													
FD	317	23	11	5	4	1	2	1	1	1	2	1	1
VD	25	5	18	24	24	27	27	28	28	28	27	28	28
R	253	1	4	5	5	6	7	6	7	5	6	5	5
Condition 8 $p(R/FD) = .4$													
FD	270	19	10	3	2	1	1	1	0	0	1	0	0
VD	80	10	19	26	27	29	28	29	29	29	28	29	29
R	122	8	13	16	17	19	17	18	18	19	18	17	17
Condition 9 $p(R/FD) = .1$													
FD	140	14	7	3	2	2	2	2	1	1	1	1	1
VD	213	15	22	26	26	28	28	27	28	27	28	28	28
R	28	14	20	22	23	24	23	22	25	23	24	24	23
Condition 10 $p(R/FD) = .5$													
FD	303	22	15	7	3	1	2	1	1	2	1	1	1
VD	50	7	14	23	25	28	27	28	28	27	28	28	28
R	160	5	9	12	13	14	16	13	16	15	16	16	13
Condition 11 $p(R/FD) = .725$													
FD	241	11	15	18	19	19	17	13	10	8	7	4	4
VD	60	13	9	6	6	6	8	11	15	17	17	20	21
R	154	6	4	3	2	3	3	4	6	7	8	7	8
Condition 12 $p(R/FD) = .2$													
FD	119	7	11	11	12	10	6	5	2	2	2	2	1
VD	179	17	14	14	13	15	19	20	22	23	23	23	24
R	35	12	9	10	9	12	13	15	15	18	16	16	18
Condition 13 $p(R/FD) = .65$													
FD	233	9	14	19	20	20	16	11	9	4	5	4	4
VD	65	16	11	6	5	5	9	14	16	21	20	21	20
R	138	8	6	3	3	2	4	5	7	9	8	9	10
Condition 14 $p(R/FD) = .3$													
FD	168	8	9	10	14	11	9	5	4	4	3	3	3
VD	143	18	15	14	10	14	15	20	21	20	21	21	21
R	60	12	10	9	6	10	10	14	15	11	12	13	14

APPENDIX

Continued.

Stimuli													
Variable-duration set													
FD	1	2	3	4	5	6	7	8	9	10	11	12	
Condition 15 $p(R/FD) = .8$													
FD	267	7	16	21	23	22	16	11	12	10	7	9	6
VD	30	18	9	5	2	3	8	14	13	15	18	16	19
R	195	5	5	2	2	1	2	5	4	6	5	6	6
Condition 16 $p(R/FD) = .1$													
FD	93	5	9	7	7	6	5	2	1	1	1	1	2
VD	209	20	16	17	17	18	20	23	24	23	23	24	23
R	22	14	13	13	13	15	15	18	19	17	19	18	18
Condition 17 $p(R/FD) = .4$													
FD	191	6	13	14	17	14	10	7	3	3	2	2	2
VD	107	19	11	11	8	10	15	18	21	22	23	23	23
R	83	12	7	6	5	6	9	11	14	14	12	15	14
Condition 18 $p(R/FD) = .5$													
FD	214	5	14	16	17	18	12	5	5	4	3	3	2
VD	71	20	12	10	8	7	14	21	20	22	22	22	24
R	109	10	7	5	5	4	7	12	10	12	13	11	13