INTERRESPONSE-TIME ANALYSIS OF STIMULUS CONTROL IN MULTIPLE SCHEDULES

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Interresponse-time distributions were recorded in two components of multiple variable-interval schedules that were varied over several conditions. Values of the exponent for power functions relating ratios of interresponse times emitted per opportunity to ratios of reinforcers obtained in the two components varied with interresponse-time class interval. The exponent (sensitivity to reinforcement) afforded a measure of stimulus control exerted by the discriminative stimuli. Exponents were near zero for short interresponse times, consistent with previous conclusions that responses following short interresponse times are controlled by response-produced or proprioceptive stimuli. Values of exponents increased with longer interresponse times, indicating strong control by exteroceptive stimuli over responses following interresponse times of approximately one second or longer.

Key words: stimulus control, interresponse time, generalized matching law, sensitivity, multiple VI VI schedules, key peck, pigeon

Discrimination is manifest as a response differential. In a multiple schedule the two main factors contributing to discrimination are the difference between successively presented discriminative stimuli and the difference between their correlated reinforcer rates. Variation in the reinforcer differential results in the ratio of responses between two components changing as a power function of the ratio of reinforcers obtained in the two components (Lander & Irwin, 1968). In logarithmic terms the power function is

$$\log \frac{P_1}{P_2} = a \log \frac{R_1}{R_2} + \log c. \quad (1)$$

In Equation 1, P and R denote numbers of responses emitted and reinforcers obtained, respectively, and the subscripts identify the components in which they occur. The constant c describes an overall bias towards responding in

one or other component. The exponent of the power function, a , describes the sensitivity with which response ratios change when reinforcers ratios are varied.

Control exercised by discriminative stimuli is traditionally assessed in terms of generalization tests (Honig & Urcioli, 1981). Variation in the dimensional values of discriminative stimuli during the generalization test may result in change in response probability. The extent of that change is given by the slope of the generalization gradient and provides a measure of stimulus control. In procedures in which discrimination is maintained between one stimulus value (S_1 , accompanied by one reinforcer rate) and several others on the same dimension (S_i , accompanied by a different reinforcer rate), the difference in response rates in S_1 versus S_i is a direct function of $S_1 - S_i$, the stimulus separation (Blough, 1969, 1972; Heinemann & Chase, 1975). The $S_1 - S_i$ response differential is also determined by the differential between reinforcer rates correlated with the different stimuli, as indicated by changes in generalization-gradient slope as a function of the reinforcer differential arranged in discrimination training (Dysart, Marx, McLean, & Nelson, 1974; Wheatley & Thomas, 1974). White, Pipe, and McLean (1983, 1984) varied both stimulus and rein-

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forcer differentials together in a series of multiple schedules and found that sensitivity to reinforcement (a in Equation 1) changed systematically with stimulus difference. Because a describes discriminative performance over a range of reinforcer differentials and is uninfluenced by the specific effects of any one differential, White et al. suggested that a might serve as a quantitative measure of stimulus control. That is, a is sensitive to functional differences between discriminative stimuli.

Other factors unrelated to dimensional stimulus value may also affect a , just as generalization-gradient slope is influenced by various procedural factors (Mackintosh, 1974; Nevin, 1973; Rilling, 1977). For example, a decreases with time since component alternation (McLean & White, 1981) and increases with higher rates of concurrently available reinforcement (McLean & White, 1983). Such influences, however, may simply place a limit on the extent to which a can vary with stimulus difference, or equivalently, may determine the absolute values of a in any given experimental situation where there is a constant stimulus difference (White et al., 1984). Whatever the cause, however, it appears that a is sensitive to the effects of nonstimulus factors that are important in determining the level of stimulus control observed.

The aim of the present study was to examine the relation between stimulus control and interresponse time (IRT). Blough (1963, 1969) and Sewell and Kendall (1965) have shown that responses following IRTs of different durations are not all subject to the same degree of stimulus control, as measured by generalization-gradient slope. Their demonstration of weaker control for short IRTs than for longer IRTs, following single-stimulus training, was extended by White (1973) to include intradimensional discrimination, although in White's study, even shorter IRTs than those reported by Blough were under stimulus control (also see Rilling, 1977). In the studies by Blough (1969) and White (1973), IRT measures took into account the fact that shorter IRTs have more opportunities to occur than do longer IRTs, by using the IRTs per opportunity (IRT/OP) statistic (Anger, 1956).

The likely reason for weaker control over responses following short IRTs is that these responses may be under strong control by the preceding response, or by proprioceptive feedback (Blough, 1969).

Given that the sensitivity parameter (a) in Equation 1 affords an index of stimulus control in multiple schedules, a is expected to vary with IRT in a way consistent with the results of the earlier studies in which generalization-gradient slope served as the measure of stimulus control. Values for a should be small for responses following short IRTs, and should increase as IRT lengthens. This possibility was examined in the present study by recording IRTs in different class intervals in two components of multiple variable-interval (VI) schedules that were varied over a range of several reinforcer differentials.

METHOD

Subjects

Five homing pigeons with a year's prior experience in a four-component multiple schedule were maintained at $80\% \pm 5\%$ of their free-feeding weights. Birds E1, E2, and E3 were about 3 years old, E4 was 5 years old, and E5 was 11 years old. Water and grit were available in the living cages and supplementary feeding ensured maintenance of the prescribed weights.

Apparatus

A sound-attenuating experimental chamber with internal dimensions of 34 x 34 x 35 cm contained an intelligence panel with a central 2.5-cm diameter translucent response key, 26 cm from the grid floor. A central hopper opening 12.5 cm below the key allowed 3-s access to wheat. There was no houselight. An exhaust fan provided masking noise. A force of 0.16 N was sufficient to operate the key and each response was followed by 0.04-s offset of the keylight. The response key could be illuminated by a 1.7-cm long and 2-mm wide white on black line, oriented horizontally or vertically. Experimental events were controlled and recorded by solid state apparatus located in an adjacent room.

Table 1
Response and reinforcer frequencies in each component summed over the last five sessions
in each multiple-schedule condition and sessions conducted in each condition.

Condition		Sessions	Responses		Reinforcers	
			Horizontal	Vertical	Horizontal	Vertical
Bird E1						
VI 48	VI 240	22	9406	6578	137	24
VI 240	VI 48	22	8224	10448	21	139
VI 60	VI 120	20	8631	9114	116	59
VI 120	VI 60	21	9266	9580	59	116
VI 80	VI 80	39	7598	10274	88	92
Bird E2						
VI 48	VI 240	23	12480	6195	140	24
VI 240	VI 48	23	7322	11595	22	133
VI 60	VI 120	21	10236	7324	118	60
VI 120	VI 60	21	8935	10421	59	118
VI 80	VI 80	21	10279	8534	86	83
Bird E3						
VI 48	VI 240	22	13813	1696	131	23
VI 240	VI 48	22	5006	12689	22	139
VI 60	VI 120	21	14017	8642	115	59
VI 120	VI 60	23	11183	11725	58	118
VI 80	VI 80	36	12860	10210	75	77
Bird E4						
VI 48	VI 240	25	4514	2031	134	21
VI 240	VI 48	24	2956	3910	24	129
VI 60	VI 120	20	4596	3599	117	56
VI 120	VI 60	21	4164	4152	59	118
VI 80	VI 80	39	3970	3327	92	88
Bird E5						
VI 48	VI 240	24	9635	6576	137	24
VI 240	VI 48	24	6834	8565	24	133
VI 60	VI 120	20	10300	9441	116	57
VI 120	VI 60	20	9690	10548	57	119
VI 80	VI 80	35	10147	9334	90	92

Procedure

Preliminary training was unnecessary owing to the birds' prior experimental history, and all birds were introduced to the first condition in the first session. Each session was comprised of 28 100-s components, with 14 presentations of the horizontal line alternating directly with 14 presentations of the vertical line. During the horizontal line, responses were reinforced according to one VI schedule; during the vertical line, responses were reinforced according to another independent VI schedule. Schedules were constructed from constant-probability progressions with values chosen to

keep total reinforcers per session approximately constant over conditions. Five multiple-schedule conditions were conducted, each for a minimum of 20 sessions and until a stability criterion was attained. Schedule values (in seconds), the order in which conditions were conducted, and the numbers of sessions required for the performance of each bird to become stable, are given in Table 1. The stability criterion was that in each of five consecutive sessions, responses in the richer component, as a proportion of total responses in both components, did not exceed $\pm 5\%$ of the mean response proportion for the five sessions.

RESULTS AND DISCUSSION

Responses and reinforcers summed over the last five sessions of each multiple-schedule condition are given in Table 1. Response frequencies followed the typical pattern for multiple schedules, with distributions of responses between the two components generally reflecting the distributions of reinforcers. Logarithms (to the base 10) of ratios of the response total are shown in Figure 1 as a function of logarithms (base 10) of ratios of reinforcers obtained in each component, for each condition. The linear function defined by Equation 1 was fitted to the log ratio data for each bird according to the method of least squares. In Figure 1, estimates for sensitivity (a) and bias ($\log c$) are given in addition to values for the standard error of the estimate (se), which indicated that in all cases Equation 1 provided a satisfactory fit to the data. Values for bias did not deviate systematically from zero. Values for sensitivity ranged from 0.14 to 0.78, consistent with sensitivity values for multiple schedules reported in previous studies (Charman & Davison, 1982; McLean & White, 1981; White et al., 1983, 1984).

Interresponse-time distributions were recorded for each component by summing IRT frequencies in nine successive 0.22-s wide class intervals within each component over the last five sessions per condition (tables of IRT frequencies may be obtained from the author). The absolute IRT frequencies for each condition are shown in Figure 2 for the nine 0.22-s wide class intervals. The 10th interval was a dump bin that included IRTs of 1.98 s or longer. The IRT distributions in Figure 2 changed systematically over the different reinforcement conditions. In general, the greatest changes in absolute IRT frequency occurred at the modal IRT value, with IRT frequencies in one component gradually decreasing with reduction of reinforcement frequency in that component, concomitant with an increase in IRT frequency with increasing reinforcement frequency in the other component. The pattern of change is consistent with the distributions described by Menlove (1975) for fewer conditions, although in Menlove's data there

Fig. 1. Logarithms (to the base 10) of response ratios as a function of logarithms of reinforcer ratios with values for sensitivity (a), bias ($\log c$), and the standard error of the estimate (se) for the straight lines best fitting data for individual birds. The large crosses represent the origin for each function.

Fig. 2. Distributions of interresponse-time frequencies over 0.22-s interresponse-time class intervals for each multiple-schedule condition.

appears to be a strong bias towards responding in one component. Previous IRT analyses of multiple-schedule discrimination have suggested that the modal IRT-class interval changes as a function of reinforcement condition (Arnett, 1973; Marcucella & MacDonall, 1977), but there is little evidence for such changes in the modes of the IRT distributions in Figure 2.

In order to assess sensitivity to reinforcement for responses following different IRT durations, IRT/OP measures were calculated to take into account the opportunity available

for IRTs to occur in a given class interval. IRT frequencies were divided by the total frequencies of IRTs in that interval and all longer intervals (including the 10th bin). Ratios were then taken of IRT/OP measures for the two components, for each IRT class interval. In Figure 3, logarithms (to the base 10) of ratios of IRT/OP for the nine IRT class intervals are shown as a function of logarithms (base 10) of ratios of reinforcers obtained in the two components of the multiple schedules. Linear functions defined by Equation 1 were fitted to these data by the method of least squares.

Fig. 3. Logarithms (base 10) of ratios of IRT/OP measures for each 0.22-s wide IRT class interval as a function of logarithms (base 10) of ratios of reinforcers obtained in whole components. Numbers of the IRT class intervals (1 to 9) are given at the right of the straight lines fitted to the data for each IRT class interval. The large crosses represent the origin for each function.

Parameter values for the best fitting straight lines, a (slope) and $\log c$ (intercept) and the standard error of the estimate (se), are shown

in Figure 3. The fits of Equation 1 to the data in Figure 3 were generally excellent. Apart from the larger values for se in the first IRT

class interval for Birds E2 and E5, standard errors were very small, especially in view of the relatively small numbers of IRTs contributing to log ratios of IRT/OP for longer IRT classes (see Figure 2).

Two main features of the log ratio functions for the nine IRT bins in Figure 3 are of interest. First, values of a for many of the IRT class intervals were higher than those in Figure 1 for all IRTs combined. This was true for bins 4, 5, 6, 7, 8, and 9 for Birds E1, E3, and E5, and for bins 3, 4, 5, and 6 for Bird E2. The function for Bird E4 was quite different from those for the other birds in that a was high for bins 1 and 2, and uniformly low for the other bins. The result for Birds E1, E2, E3, and E5 suggests that IRTs from class intervals up to 0.44 s (and perhaps 0.66 s) may have served to flatten the functions for overall responding in Figure 1. Second, a changed systematically over IRT class intervals, notwithstanding individual differences in the specific nature of the change. Values for a are shown in Figure 4 for the nine 0.22-s wide class intervals to illustrate the changes more clearly. For all birds except E4, a was about zero for the shortest IRTs (0 to 0.22 s), and increased to moderately high values for longer IRTs in the region of 1 s. The analysis summarized in Figure 3 was also conducted for log ratios of IRT frequencies, rather than IRT/OP measures. The patterns of change in a with IRT class interval were overall very similar to those shown in Figure 4, with the main exceptions that a values were overall higher, and that for Birds E2 and E3, following an increase in a from short to intermediate IRT bins, there was a decrease in a for long IRTs. Also, there were negative values of a (for all birds except E4) in the 10th bin (and in bins 7, 8, and 9 for E2) owing to more IRTs in the longest class interval for the lean schedules than for the rich schedules. Interpretation of the analysis based on IRT frequencies is difficult, however, because the analysis does not take into account the change in opportunities for occurrence of IRTs in the different class intervals.

The import of the present analysis is that the changes in a shown in Figures 3 and 4 are

Fig. 4. Values for sensitivity to reinforcement for IRT/OP functions as a function of successive 0.22-s IRT class intervals.

a function of IRT class interval. The independent variable in the regression analysis was the log ratio of reinforcers obtained in each component. It can be asked whether the log ratios of IRT/OP measures were influenced by log ratios of reinforcers obtained by responses following IRTs of different durations. Distributions of reinforcers obtained by responses in each IRT class interval were not collected in this experiment, but expected distributions can be obtained by simulation. It is obvious, however, that even over the total of 7000 s of exposure to each component in each condition, relatively few reinforcers would have been obtained in each IRT class, and their distribution would therefore show great random fluctuation from bird to bird, session to ses-

sion, and condition to condition. Monte Carlo simulations using the observed IRT distributions confirmed that there were substantial variations in the frequencies and hence ratios of reinforcers obtained following IRTs of different durations, even though session-by-session variation in the simulated total obtained reinforcers per component was extremely small (S. E. G. Lea, personal communication, October 1, 1984). Yet the functions in Figure 3 exhibit remarkably little error variance in the relation between log ratios of reinforcers obtained over whole components. If the log ratios of IRT/OP measures were influenced by log ratios of reinforcers obtained in the different IRT class intervals, the functions in Figure 3 would have exhibited considerable error variance. It is therefore unlikely that ratios of IRT/OP measures were sensitive to ratios of reinforcers in the different IRT class intervals. A future study in which reinforcers are recorded for different IRT class intervals might verify this expectation, although many more sessions per condition (in excess of 100) would be required to collect the data necessary to generate determinate log ratios of reinforcers for each IRT class.

In general, the present analysis suggests that sensitivity to reinforcement is low for short IRTs, and is high for IRTs of approximately 1 s and longer. This generalization is consistent with an interpretation of a as a measure of stimulus control (White et al., 1983, 1984). Blough (1969) and Ray and Sidman (1970) have suggested that responses following short IRTs are primarily determined by the preceding response—that is, by proprioceptive feedback rather than by exteroceptive stimuli. Blough (1969) generated generalization gradients for two birds by reinforcing responses in the presence of a single wavelength (582 nm) and presenting in extinction several other wavelengths (1 nm apart) either side of the 582-nm wavelength. Each response was followed by 0.4-s stimulus offset. Gradients based on the IRT/OP measure for responses following IRTs between 0.6 s and 1.0 s were flat, indicating no stimulus control for IRTs up to 1 s. For IRTs beyond 1 s, gradients were steeper. In the present study, values for a were

generally very low up to IRTs of 0.66 s (with the exception of E4) and increased up to IRTs of 1.10 s. Using generalization-gradient slope as the index of stimulus control, White (1973) also reported control for IRTs of less than 1 s. The reason that stimulus control was absent for IRTs between 0.6 and 1 s in Blough's (1969) study, whereas there was clear evidence for stimulus control over the same range of IRTs in both the present and the earlier (White, 1973) study, may be related to Blough's use of a 0.4-s offset of the keylight following each response. Because the 0.4-s absence of stimulus presentation precludes the recording of IRTs shorter than 0.4 s, it could be argued that IRT durations in Blough's study should be interpreted in terms of the duration available for their occurrence. That is, stimulus control in Blough's study could be regarded as being absent for IRT class intervals up to 0.6 s, a conclusion that is consistent with the present data.

Although there is little evidence from the present data to suggest that a decreases with longer IRTs, such a reduction might have been expected in that longer IRTs are associated with increased likelihood of time being allocated to behavior other than key pecking (McLean & White, 1983). That is, stimuli controlling "other" behavior will compete with the control exerted over key pecking by the discriminative stimuli. Consequently, values for a might be low for long IRTs. In the present study, the longest IRT recorded was 1.98 s, excluding IRTs greater than 1.98 s in the dump bin. A convincing demonstration of a reduction in a with long IRTs would require recording IRTs over a range of several seconds.

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