STIMULUS CONTROL OF DIFFERENTIAL-REINFORCEMENT-OF-LOW-RATE RESPONDING¹

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Five pigeons were given single-stimulus training on an 8-sec differential-reinforcement-of-low-rate schedule followed by steady-state generalization training using 12 wavelength stimuli. Three birds had a high percentage of reinforced responses on the training schedule and flat generalization gradients of total responses. The birds with fewer reinforced responses had much steeper generalization gradients. Generalization gradients plotted as a function of both stimulus wavelength and interresponse time showed that for most birds, stimulus control was restricted to responses with long interresponse times. Responses with very short interresponse times were not under stimulus control and there was some evidence of inhibitory control of short interresponse times. Interresponse-times-per-opportunity functions, plotted as a function of stimulus wavelength, showed that stimulus wavelength controlled the temporal distribution of responses, rather than the overall rate of response. The data indicate that the differential-reinforcement-of-low-rate schedule generates several response categories that are controlled in different ways by wavelength and time-correlated stimuli, and that averaging responses regardless of interresponse-time length obscures this control.

Key words: differential reinforcement of low rate, stimulus control, interresponse time, response rate, inhibitory control, key peck, pigeon

Studies investigating the stimulus control of responding maintained by a differential-reinforcement-of-low-rate (DRL) schedule have concluded that external stimuli gain little control over DRL responding. Hearst, Koresko, and Poppen (1964) found that generalization gradients of line orientation were much flatter and more irregular in shape following DRL training than following variable-interval (VI) training. Zeiler (1969), using a steady-state generalization procedure and within-subjects comparisons, concluded that DRL schedules produced less control of responding by the positive stimulus than fixed-interval (FI), VI, fixed-ratio (FR), or variable-ratio (VR) schedules.

A common explanation for the reduction in gradient steepness following DRL training is the "internal cues" hypothesis proposed by Hearst (1965, 1969), which maintains that

DRL responding is controlled by proprioceptive stimuli from collateral behavior that occurs between responses and that control by these internal stimuli reduces or prevents control by external stimuli. The "internal cues" hypothesis has been extended to account for the flat gradients obtained under VR schedules, in which proprioceptive feedback from rapid responding is assumed to control responding, and long VI schedules, which presumably have a higher incidence of collateral behavior than shorter VI schedules (Haber and Kalish, 1963; Thomas and Switalski, 1966).

This analysis of DRL generalization follows traditional definitions of stimulus control (*e.g.*, Terrace, 1966) in assuming that flat generalization gradients reflect the absence of control by the stimuli being varied. This interpretation of gradient steepness is valid if one can assume that the response measure (response rate in almost all cases) reflects a homogenous response class. If, however, response rate is not a unitary measure, *i.e.*, if all responses are not controlled in the same way by stimuli, then gradients with flat or intermediate slopes may reflect the averaging of several response categories or patterns of stimulus control, rather than the absence of control (Blough, 1965).

¹This paper was presented at Eastern Psychological Association, Atlantic City, 1970. D. S. Blough and P. M. Blough contributed valuable guidance and support in all phases of the study. The research was supported by NIMH Grant MH-02456 awarded to D. S. Blough. Reprints may be obtained from the author, Department of Psychology, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3.

An alternative to the hypothesis that DRL responding is controlled only by internal stimuli is the idea that DRL responding is controlled by external stimuli, but the usual measures of response strength are insensitive to such control. Data supporting this hypothesis come from situations in which intermediate response rates in generalization resulted from the combination of several classes of behavior (Migler, 1964; Migler and Millenson, 1969) or the interaction of control by more than one source of stimuli (Ray and Sidman, 1970). Since a DRL schedule involves differential reinforcement of responses on the basis of inter-response time (IRT) length, it might favor the development of more than one response class. In addition, there are several types of potential stimuli in the DRL situation (*e.g.*, external stimuli, time-correlated stimuli, and proprioceptive stimuli) that might interact in controlling the various response classes.

The present study therefore used detailed IRT analyses to investigate stimulus control functions obtained under a DRL schedule. To obtain enough data to permit reliable IRT analyses and to avoid confounding measures of stimulus control with measures of extinction, a steady-state generalization procedure involving repeated measurements of DRL responding as a function of stimulus change was used.

METHOD

Subjects

Five naive White Carneaux pigeons were maintained at approximately 80% of their free-feeding weights.

Apparatus

Three standard single-key Lehigh Valley pigeon chambers, equipped with loudspeakers supplying white noise, were used. The response keys were operated by a force of about 14 g (0.14 N).

The stimuli were produced by a Bausch and Lomb 250-mm grating monochromator equipped with a ribbon filament lamp operated at 17 amp ac and set to pass a band width of 6.6 nm. The monochromatic light was then passed through three fiber optics light guides of 3 mm diameter to form a fuzzy spot of 9 mm diameter centered on each key. The luminance of the spot was approximately 21

cd/m² at 570 nm. There was no other illumination in the chambers. The equipment was monitored by a LINC computer.

Procedure

The first phase of the experiment consisted of single-stimulus training on a DRL 8-sec schedule of reinforcement. Each daily session consisted of 112, 45-sec presentations of the training stimulus, 570 nm, separated by 3-sec intertrial intervals during which the key was dark and responses had no effect. The key was also dark during reinforcements. On the DRL schedule, a response was reinforced only if it occurred at least 8 sec after (1) the preceding response, (2) the onset of the stimulus, or (3) the end of a reinforcement. Birds 1, 2, and 3 were removed before the end of the session if they had received over 100 reinforcers, but Birds 4 and 5, which received many fewer reinforcers, were always given the entire 90-min session.

On the first day, the key-pecking response was shaped and 50 reinforcers were given on a CRF schedule. During the next three days, the DRL requirement was gradually increased from 4 sec to 8 sec, the reinforcement time was decreased from 5 to 2.5 sec, and the houselight was faded out. The reinforcement time for Birds 1, 2, and 3 was later decreased to 2 sec to maintain stable weights; this change did not affect performance. After 30 days of training, Birds 4 and 5 were receiving very few reinforcers and a shaping procedure was attempted with Bird 5. The DRL requirement was decreased to 4 sec and then gradually increased over the next 19 days to the original 8-sec requirement. This procedure produced only a slight, transitory improvement in performance and no further attempts at shaping were made. Single-stimulus DRL training was continued until all birds had maintained a stable IRT distribution for at least 14 days (63 to 78 days).

In the second phase, the birds were transferred to a steady-state generalization procedure. Each generalization session was initiated by four presentations of 570 nm, during which responses were reinforced on the DRL 8-sec schedule. The remainder of the session consisted of 11 series of 16 stimulus presentations per series. During each series, 12 test stimuli, ranging from 560 nm to 582 nm in 2-nm steps and including 570 nm, were presented in ran-

dom order without reinforcement for 45 sec each. Interspersed with the 12 test stimuli were four presentations of the training stimulus (570 nm), during which responses were reinforced on the DRL 8-sec schedule. Steady-state generalization sessions were continued until the daily generalization gradients and IRT distributions for each bird were stable over at least 18 days (36 to 48 days).

Data Analysis

The data, IRTs coded by bird and stimulus and recorded sequentially on magnetic tape, were analyzed by stored programs on the LINC. All analyses omitted the initial four stimulus presentations with reinforcement available and the first generalization series. Interresponse-time analyses included both the time between two successive responses and the time between the termination of a reinforcement and the next response. The time preceding the first response after stimulus onset was not included in the analyses. In the initial analyses, IRTs were classified into 16, 1-sec bins labelled as Bins 0 through 15, referring to the lower boundary of the bin. For example, Bin 0 contains all IRTs longer than 0 sec and shorter than 1 sec. The terminal IRT bin, Bin 15, contains all IRTs equal to or longer than 15 sec. In subsequent analyses several 1-sec bins were, for clarity of presentation, combined to form one longer bin.

In most cases, IRT distributions are presented using the IRTs per opportunity (IRTs/op) transformation. In a given period of time there are more opportunities for short IRTs to occur than for long IRTs, especially in procedures involving brief stimulus periods, which impose an additional bias against long IRTs. Interresponse times per opportunity is a transformation of the raw IRT frequency distribution that takes into account the decrease in the number of opportunities for an IRT to occur as a function of the length of the IRT and is an estimation of the conditional probability that a response with a certain IRT will occur, given that the necessary time has elapsed. The computation of IRTs/op involves dividing the number of IRTs in a bin by the number of IRTs in that bin plus the IRTs in all longer bins. (See Anger, 1956, for a complete discussion of the IRTs/op transform.) In interpreting IRTs/op distributions, it must be remembered that the number of

opportunities decreases as IRT length increases, and therefore the points for the longer IRTs in a distribution are less reliable than points for shorter IRTs. The IRTs/op analyses presented here were performed on the mean IRT frequency distributions over the last 18 days of testing; data points based on fewer than 20 opportunities have not been plotted.

RESULTS

Since this paper is concerned with the stimulus control of DRL responding, only the data from the last 18 days of stable performance on steady-state generalization are presented. Control by the temporal contingencies of the DRL schedule can be assessed by IRT analyses of responding during the presentations of 570 nm that were correlated with reinforcement. Figure 1 shows distributions of relative IRT frequency (top half) and IRTs/op (bottom half). Shorter than 1-sec IRTs are represented by striped bars and longer than 8-sec IRTs (*i.e.*, reinforced responses) are represented by solid bars.²

The outstanding feature of the relative frequency distributions, common to all birds, is the high percentage of responses with IRTs shorter than 1 sec (Bin 0). The distributions of responses with longer IRTs show a clear discontinuity between the first three birds and the last two birds. The first three birds show considerable control by the temporal contingencies of the DRL schedule with a relatively high proportion of their responses meeting the 8-sec criterion for reinforcement; the percentage of total responses with IRTs in Bins 8 to 15 was 36.6, 33.8, and 21.8 for Birds 1, 2, and 3, respectively. In contrast, Birds 4 and 5 had less efficient DRL performance, with only 4.8% and 4.1% of the total responses meeting the criterion for reinforcement.

The IRTs/op distributions show that, in spite of the wide discrepancies in the proportion of reinforced responses, all birds developed some degree of temporal discrimination; the conditional probability of IRTs in Bins 8 to 14 was consistently higher than the conditional probability of IRTs in Bins 1 to 7 for all five birds. The differences in degree of

²Tables of the raw data from which Figures 1, 2, 3, and 4 were derived may be obtained from the author.

Fig. 1. Relative IRT frequency (top half) and IRTs/opportunity (bottom half) distributions for responding during reinforced presentations of 570 nm during the last 18 days of steady-state generalization for each of the five birds. Shorter than 1-sec IRTs are represented by striped bars and longer than 8-sec IRTs (*i.e.*, reinforced responses) are represented by solid bars. In the IRTs/opportunity distributions, data points based on fewer than 20 opportunities have been omitted.

temporal discrimination across birds are most clearly reflected by an increase from Bird 1 to Bird 5 in the conditional probability of IRTs in Bins 1 to 7.

Figure 2 shows the wavelength generalization gradients based on the mean number of responses emitted in the presence of each of the 12 test stimuli presented without reinforcement over the last 18 days of testing. Birds 1, 2, and 3 show relatively flat gradients, with only 9 to 11% of the generalization responses occurring at 570 nm. The gradients for Birds 4 and 5 are much steeper, with 21 and 20% of the responses occurring at the training stimulus. There was a sizeable negative correlation ($r_s = -0.9$) between gradient steepness and temporal control by the DRL schedule; the birds with the steepest gradients (as measured by the percentage of test responses emitted to 570 nm) had the lowest percentage of reinforced responses on the DRL schedule; the

birds with flat gradients had a higher percentage of reinforced responses.

Figure 3 shows generalization responses plotted as a joint function of IRT length and stimulus wavelength. To generate this figure, the IRT frequency distribution for each of the 12 test stimuli was first converted to an IRTs/op distribution. The IRTs/op value was then plotted as a function of wavelength, generating a wavelength generalization gradient for each IRT bin. For clarity of presentation, IRT bins of 1-sec duration that had similar shapes have been combined to form wider IRT bins.³ It should be noted that the gradient shapes

³In order to compare IRTs/op values for bins of various sizes, the IRTs/op values for longer than 1-sec bins were transformed by the formula $A = 1 - \sqrt{1 - K}$, where K = the IRTs/op value obtained for an n -sec bin and A = the transformed IRTs/op comparable to a 1-sec bin value.

Fig. 2. Percentage of the total number of unreinforced test responses emitted during the last 18 days of steady-state generalization for each of the five birds.

shown in Figure 3 are not a function of the IRTs/op transform and are clearly evident when absolute number of responses rather than IRTs/op are plotted.

The gradients shown in Figure 3 suggest the division of responses, defined in terms of IRTs, into three general classes on the basis of the way in which they are controlled by wavelength. The most distinct response class consists of the responses with very short (shorter than 1-sec) IRTs. The gradients for Bin 0 IRTs are flat for all five birds, showing a high probability of occurrence but no control by wavelength. In some cases, the Bin 0 gradients are slightly similar in shape to the Bin 1-2 gradients. This is because arbitrary bin boundaries do not always correspond exactly to the organism's response categories. The finer-grained IRT distributions obtained by Blough and Blough (1968) indicate that the functional upper limit for these very short IRTs is probably closer to 0.8 sec. Although Bin 0 responses have a high probability and are not controlled by wavelength, they constitute a constant proportion of the total responses emitted at each wavelength value (the IRTs/op value at the shortest IRT bin is equivalent to the percent-

age of total responses value for that IRT bin), and thus do not affect the shape of the gradients of overall response rate shown in Figure 2. There was no change in the gradients shown in Figure 2 when the Bin 0 IRTs were omitted.

The second response class consists of responses with either V-shaped or flat gradients and the third class consists of responses with peaked gradients showing a maximum at or near 570 nm. The dividing point between these two classes of responses varies across birds. For Birds 1, 2, and 3 all responses with IRTs longer than 1 sec but shorter than 8 sec (Bins 1-2, 3-4, and 5-6-7) have either V-shaped or flat gradients. Of particular interest is the sharp and symmetrical inverse gradient in Bin 1-2 for Bird 1. All three birds show more shallow inverse gradients in Bin 3-4. The remainder of the shorter than 8-sec IRT gradients for these birds are flat. In contrast, all IRTs longer than 8 sec show relatively steep peaked gradients.

Birds 4 and 5 show a much earlier transition from flat to peaked gradients; the flat gradients are restricted to shorter than 5-sec IRTs for Bird 4 (Bins 1-2 and 3-4) and to shorter than 3-sec IRTs for Bird 5 (Bin 1-2). The remainder of the gradients are peaked. Since very few responses with longer than 12-sec IRTs were emitted by Birds 4 and 5, the data points for Bin 13-14 have been omitted.

Figure 3 indicates that the shape of the wavelength generalization gradient changes depending on the length of the IRT. To clarify the relationship between stimulus wavelength and IRT length, representative portions of the data from Figure 3 were replotted to show an IRTs/op function (excluding Bin 0 responses) for seven of the 12 wavelengths for each of the five birds (Figure 4). This graph demonstrates that the distribution of IRTs is controlled by stimulus wavelength. The IRT distributions at 570 nm, the training wavelength, show temporal discriminations with high conditional probabilities of IRTs longer than 8 sec. The distributions change to more constant IRTs/op functions as a function of distance from the training wavelength. This change is clearest in the distributions for Birds 1, 2, and 3, which show a decrease in the conditional probabilities of longer than 8-sec IRTs and an increase in the conditional probabilities of shorter than 8-sec IRTs as a func-

Fig. 3. Generalization gradients of conditional response probability (IRTs/op) as a function of stimulus wavelength and IRT length. The dotted vertical line indicates the stimulus that was correlated with reinforcement during single-stimulus training and steady-state generalization. Data points based on fewer than 20 opportunities have been omitted.

tion of stimulus change. Birds 4 and 5 show similar changes in the IRT distributions, except that the conditional probabilities of Bins

5-6-7 also decrease as a function of stimulus change and the conditional probabilities of shorter IRTs remain relatively constant.

Fig. 4. Conditional response probability (IRTs/op) functions for seven of the 12 wavelengths. Longer than 8-sec IRTs are represented by solid bars. Data points based on fewer than 20 opportunities and points for Bin 0 responses have been omitted.

DISCUSSION

Three of the five birds in the present study had the flat generalization gradients typically

associated with DRL training. Comparison of Figure 1, showing IRT distributions during reinforced presentations of the training stimulus, and Figure 2, showing gradients of total

responses, demonstrates a clear relationship between schedule performance and gradient steepness. The birds with the highest percentage of reinforced responses had the flattest gradients; birds with less efficient DRL performance had much steeper gradients. At first glance, this relationship between gradient steepness and DRL performance appears to support the "internal cues" hypothesis, which predicts that an increase in control by the temporal contingencies of the schedule should decrease the amount of control exerted by wavelength. However, generalization gradients plotted as a function of IRT length (Figure 3) show that for the three birds with efficient DRL performance, peaked gradients are restricted to long IRT responses, with V-shaped or flat gradients for shorter IRTs. When these responses are averaged, the result is a flat generalization gradient. The two birds with less control by the DRL contingencies have peaked gradients for a much larger proportion of their test responses, and thus have steeper gradients of response rate.

These data indicate that rate of response is not an appropriate measure of stimulus control in the DRL situation. The IRTs/op functions plotted as a function of stimulus wavelength (Figure 4) demonstrate that stimulus wavelength controls the distribution of IRTs, rather than the overall response rate. The slope of the gradients based on response rate (Figure 2) reflects the proportion of responses that have peaked wavelength gradients, rather than the amount of control by wavelength. Thus, averaging responses regardless of IRT length obscures evidence of stimulus control. On the basis of these data, it seems that the appropriate question to ask when evaluating the effects of schedule of reinforcement on stimulus control is not "how much stimulus control?" but instead "what kind of stimulus control?" and "control of which responses?": detailed IRT analyses are helpful in this regard.

There are several possible interpretations of these data. The first possibility is that the pecking response is under the control of wavelength and time-correlated stimuli. If a DRL schedule is considered as a stimulus discrimination problem with time-since-the-last-response as the discriminative stimulus, then the changes in gradient shape as a function of IRT length can be viewed as the product of an interaction

of control by both time-correlated stimuli and wavelength. The most interesting implication of this interpretation is that the same stimulus dimension, wavelength, exerts both excitatory control and inhibitory control of pecking—excitatory control when combined with positive time-correlated stimuli, as shown by steep peaked gradients at long IRTs, and inhibitory control when combined with negative time-correlated stimuli, as shown by V-shaped gradients at short IRTs. According to some definitions of inhibition (Hearst, Besley, and Farthing, 1970; Jenkins, 1965), the low-probability flat gradients at shorter IRTs can also indicate response inhibition. The earlier transition from flat to peaked gradients in Birds 4 and 5 reflects a less accurate discrimination between positive and negative temporal stimuli.

The second possibility is that wavelength controls some hypothetical, nonpecking behavior, which in turn controls pecking. Several investigators (*cf.* Zuriff, 1969) have suggested that the source of time-correlated stimuli in a DRL schedule resides in the proprioceptive stimuli from the collateral behavior often observed to occur between responses. This behavior is presumably maintained by adventitious reinforcement, since it increases the probability of reinforced long IRTs. The strongest statement on the role of collateral behavior in DRL, incorporated in Hearst's "internal cues" hypothesis, is that pecking is controlled primarily by stimuli from preceding collateral behavior and not by external stimuli. The present results are not necessarily incompatible with the hypothesis that pecking is not controlled by wavelength. However, Figures 3 and 4 indicate that if one assumes that the temporal distribution of pecking is controlled only by collateral behavior, then it is also necessary to assume that the collateral behavior is controlled by wavelength. If long IRTs indicate a high probability of collateral behavior, then the peaked gradients for long IRTs reflect a decrease in collateral behavior as a function of stimulus distance. If collateral behavior does mediate pecking, then a decrease in the collateral behavior would result in an increase in short IRT pecks, as seen in Figure 4, and might produce the V-shaped gradients of shorter IRTs seen in Figure 3.

A third possibility, also involving collateral

behavior, is that both pecking and collateral behavior are controlled by wavelength and by time-correlated stimuli. The suggestion that collateral behavior is often the source of time-correlated stimuli controlling pecking does not eliminate the possibility that pecking is controlled by wavelength as well. Indeed, on the basis of proximity to reinforcement one might expect that wavelength would exert more control over pecking than over collateral behavior. Although it is difficult to specify how this control would be reflected in the IRT gradients of the present study, it is possible that a sloping gradient of decreasing response probability, which reflects control by wavelength, would interact with the V-shaped gradient of increasing response probability, which reflects control by collateral behavior, as explained above, and might produce the flat gradients as seen for intermediate IRTs (Bin 5-6-7) for Birds 1, 2, and 3.

The crucial difference between these interpretations involves the function of collateral behavior in a DRL schedule, *i.e.*, whether collateral behavior is the source of the time-correlated stimuli that control pecking and whether the control of pecking by collateral behavior eliminates control by wavelength, as in the second alternative, or interacts with control by wavelength, as in the third alternative. To distinguish between these alternatives it is necessary to know more about the behavior that occurs between pecks and how the probability of that behavior changes as a function of changes in wavelength. Experiments such as Laties, Weiss, and Weiss (1969) and Schwartz and Williams (1971) that involved specification and measurement of collateral behavior are promising in this regard.

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Received 16 August 1974.

(Final Acceptance 20 November 1975.)