*DISCRETE AND CONTINUOUS MEASURES OF
DIMENSIONAL STIMULUS CONTROL*

JOHN M. HINSON AND JENNIFER J. HIGA

WASHINGTON STATE UNIVERSITY

In two sets of experiments, we examined dimensional stimulus control of pigeons' responses to a visual flicker-rate continuum. In the first experiment, responses to a single key were reinforced periodically during stimuli from one half of the stimulus continuum, and responses during other stimuli were extinguished. In the second experiment, two response keys were simultaneously available, with reinforcement for each response alternative associated with different halves of the stimulus continuum. Conditions of the second experiment involved either free-operant or discrete-trial stimulus presentations. Results from these experiments show that positive dimensional contrast appeared in discrimination tasks with one or two response alternatives, but only with free-operant procedures. In addition, discrimination between stimulus classes established by differential reinforcement was assessed as accurately by continuous rate measures as by discrete response choice in the two-alternative situation. The general implication of these experiments is that response rate measures, when properly applied, may reveal sources of variation within stimulus classes, such as dimensional contrast, that are not evident with discrete measures.

Key words: dimensional stimulus control, dimensional contrast, maintained generalization, discrete trials, flicker rate, key peck, pigeons

Modern studies of dimensional stimulus control in animals have relied heavily on two investigatory techniques. The older of the two, the transient generalization testing technique pioneered by Guttman and Kalish (1956), has been used extensively to try to relate discriminative performance to stimulus discriminability (see Honig & Urcuioli, 1981). A more recently developed method, the maintained generalization technique, has been employed in similar settings (e.g., P. Blough, 1972). Both techniques involve the construction of empirical stimulus-control gradients based on responses made during a sampling interval. Many workers now prefer the maintained procedure because of the stability of maintained gradients over many experimental sessions. Also, maintained gradients make it easier to observe the time-based changes in performance characteristic of discrimination learning (D. S. Blough, 1975; Malone, 1975).

A common finding in studies using the maintained generalization technique is dimensional contrast (see D. S. Blough, 1975; Ca-

tania & Gill, 1964; Malone & Staddon, 1973; Reynolds, 1961). Dimensional contrast refers to the relative enhancement of response differences in certain regions of empirical stimulus-control gradients despite equivalent conditions of reinforcement. Positive dimensional contrast refers to increased responding during positive (S+) stimuli near the border with negative (S-) stimuli, relative to S+ stimuli farther removed from S-. Negative dimensional contrast refers to decreased responding during S- stimuli near the border with S+, relative to S- farther removed from S+. Dimensional contrast is reminiscent of peak shift effects observed using the transient generalization testing technique (e.g., Hanson, 1959), although the theoretical relation between the two is still unclear (D. S. Blough, 1975).

A major reason for interest in dimensional contrast is that these effects violate common intuitions about the relationship between stimulus similarity and discrimination performance. For example, members of the set of S+ values that are more similar to S- appear to be discriminated better than less similar values. That is, these S+ values maintain consistently higher response rates than do S+ values farther from S- on the stimulus continuum. The absence of monotonicity between stimulus dissimilarity and discrimination measures is indeed intriguing and contrary to the

This research was supported by funds provided by the Washington State University grant-in-aid program and by NIMH grant MH40275-01 to Washington State University. Address correspondence and reprint requests to J. M. Hinson, Department of Psychology, Washington State University, Pullman, Washington 99164-4830.

predictions of most popular theories of dimensional stimulus control (D. S. Blough, 1983; Hinson, 1988).

Although dimensional contrast is observed with a variety of reinforcement schedules and dimensional continua, it has always been measured in terms of a continuous, free-operant dependent measure, such as response rate. The theoretical interpretation of response rate in stimulus-control studies has always been problematic (e.g., D. S. Blough, 1965, 1983; Honig & Urcuioli, 1981). Theorists are usually willing to accept ordinality between response rates maintained by different stimulus values and values of the hypothetical discrimination scale. But it is precisely this interpretation that makes the enhanced response-rate differences observed in dimensional contrast so puzzling, for it suggests that more similar stimuli are better discriminated from one another.

One way to avoid the problem posed by dimensional contrast is to reject response rate as a legitimate measure of discrimination. Because response rate can be influenced by many variables, discrete-trial procedures have become a popular alternative. These procedures use discrete response measures typical in psychophysical studies, such as a yes/no or presence/absence judgment of one of a number of exclusive response categories (e.g., Chase, 1983; Heinemann, Avin, Sullivan, & Chase, 1969; Heinemann & Chase, 1975). Nevertheless, this option ignores the body of literature that indicates that, under the right conditions, response rate is a sensitive dependent measure adaptable to precise, quantitative analysis (e.g., Nevin, 1984).

Rather than rejecting the continuous response-rate measure altogether, it seems wiser first to compare discrete and continuous measures of dimensional stimulus control to appreciate better their relative efficacy. The present studies directly compare these two types of measures in discrimination tasks with single or dual response alternatives. In addition, comparisons are made between free-operant and discrete-trial discrimination tasks and between certain or probabilistic payoff in a discrete-trial setting. Use of two response alternatives offering equivalent reinforcement was designed to minimize any asymmetrical effects of responding versus not responding that may occur in single-response tasks. The two alternative procedures also afforded the opportu-

nity to examine additional dependent response measures in the continuous procedure.

EXPERIMENT 1

Experiment 1 was designed to provide a first basis of comparison for different measures of dimensional stimulus control. Several positive and negative stimuli were arranged along a visual flicker-rate continuum. Stimulus values and reinforcement frequencies were chosen to try to best establish reliable positive dimensional contrast effects.

METHOD

Subjects

Six male and 2 female homing pigeons served as subjects. Birds 1 through 4 were experimentally naive prior to this experiment, and Birds 5 through 8 had varied training histories, none of which included dimensional discrimination learning. The subjects were maintained at 80% of their laboratory free-feeding weights.

Apparatus

Experiments were carried out in a standard Plexiglas and aluminum operant conditioning chamber. The internal dimensions of the chamber were 30 cm by 30 cm by 32 cm. A Gerbrands translucent pecking key, 2 cm in diameter, was affixed to the center of the front wall about 27 cm above the floor. A 6-W houselight provided diffuse illumination throughout the chamber during experimental sessions. A 5 cm by 4 cm aperture 15 cm below the key provided access to a food magazine. Mixed grain presented for 3 s was used as a reinforcer. The experimental chamber was housed in a larger sound-proofing box that contained a fan for ventilation and masking of extraneous noise. Experimental events and data collection were controlled by a microcomputer in the same room.

Procedure

After preliminary autoshaping in the chamber for both naive and experienced birds, we exposed the subjects to a 24-stimulus maintained generalization procedure. The stimuli were rates of flicker of a yellow flasher light-emitting diode (LED) with a peak wavelength of 580 nm. The LED appeared 2 cm behind a translucent pecking key. The luminance of

the steady LED was 10 cd/m². Duty cycle of the flickering LED was equal on and off. The frequency of the stimulus varied from 4 to 27 Hz, in equal 1-Hz intervals.

Preliminary work with other pigeons in this apparatus (Hinson, 1988; Hinson & Lockhead, 1986), and other assessments (Graf, 1973) were used to select stimulus values. Like people, pigeons are probably most sensitive to flicker rates within the 10- to 30-Hz range, and sensitivity seems to drop off at the extremes. To a first approximation, the 12 stimulus values on the higher end of the continuum should be in close to equally discriminable steps.

During the baseline condition, responses during all stimuli were reinforced according to a constant-probability variable-interval 60-s schedule (VI 60 s). During the discrimination condition, the lower 12 stimulus values were designated S⁻, and responses during these presentations were never reinforced (EXT). The higher 12 values were designated S⁺, and responses during these stimuli were reinforced according to the same VI 60-s schedule operative during baseline.

A single session consisted of 120 30-s stimulus presentations. Each stimulus appeared five times during the session, but otherwise the sequence of stimuli was determined by a pseudorandom process and changed daily. The baseline condition (VI 60 s all stimuli for 40 sessions) was followed by the discrimination condition (VI 60 s Stimuli 13 through 24, EXT during Stimuli 1 through 12 for 28 sessions).

RESULTS AND DISCUSSION

The pattern of results for all subjects was similar during the discrimination condition, although individual differences in overall response rate and relative response rate among stimuli did exist. Discrimination performance for all subjects appeared stable after 2 weeks and showed no large fluctuations or systematic changes for the next 2 weeks. Figure 1 shows results from baseline and discrimination conditions in the form of maintained generalization gradients for the 8 subjects. These empirical gradients represent the mean response rate of the 8 birds during each stimulus value, averaged over the last five sessions of the baseline and discrimination conditions.

As revealed by Figure 1, there were essentially no differences in responding among stimuli in the baseline condition. In the discrimi-

Fig. 1. Maintained generalization gradients for the group of 8 birds in Experiment 1. Flicker frequencies in Hz appear along the x axis. Mean response rates for the last five sessions of the discrimination condition (O) and baseline (*) are displayed. The vertical line between 15 and 16 Hz shows the division between S⁻ and S⁺.

nation condition, overall rate differences between S⁺ and S⁻ were fairly large, especially beyond three or four stimulus values on either side of the S⁻/S⁺ border. Mean response rates in S⁺ were all above the prior baseline level, whereas most S⁻ rates (with the exception of the two border values) were below baseline.

For present purposes, the most important feature of Figure 1 is the clear positive dimensional contrast effect. That is, response rate increased with flicker frequency until 24 Hz. After this stimulus value, response rate decreased. The magnitude of dimensional contrast is best represented by the degree of deviation from monotonicity in response rates during S⁺ values with increasing difference from S⁻. For the mean gradient, the change in response rate from the peak stimulus of the S⁺ function to the extreme stimulus value is approximately 15%. Differences in response rates during the peak stimulus in the mean gradient (24 Hz) and the extreme stimulus (27 Hz) were significant according to a one-way

Fig. 2. Individual maintained generalization gradients for representative birds from Experiment 1. Flicker frequencies in Hz appear along the x axis. Mean response rates for the last 10 sessions of the discrimination condition (O) and baseline (+) are displayed. The vertical line between 15 and 16 Hz shows the division between S- and S+.

analysis of variance (ANOVA), $F(1, 14) = 35.37, p < .05$.

Figure 2 provides individual maintained gradients for representative subjects from Experiment 1, based on the last 10 sessions of baseline and discrimination conditions. Base-

line responding is reasonably uniform across stimulus values for each bird. Gradients for all birds show positive dimensional contrast, although the peak stimulus and sharpness of the function differ among individuals. The magnitude of dimensional contrast varies from

about 15% to 18% of peak responding, regardless of differences in overall response rate. Slopes of the individual gradients in the border region between S- and S+ are similar, with the exception of Bird 3.

Results from Experiment 1 show that reliable positive dimensional contrast effects can be obtained within the chosen experimental parameters. All subjects quickly discriminated S- and S+ stimulus classes in this task. The peaks in the empirical gradients for individual subjects appeared in approximately the same area of the flicker-rate continuum. It should also be noted that there was no indication of negative dimensional contrast among extinction stimuli in Experiment 1. This result is common (e.g., Farthing, 1974) and appears to be due to a measurement problem when EXT is the operative schedule in S-. Negative dimensional contrast is most readily observed with a nonzero level of reinforcement during S- (e.g., Blough & Blough, 1985) that provides an adequate baseline of responding against which to measure the negative effect. Overall, the pattern of results in Experiment 1 is consistent with prior studies that have observed positive dimensional contrast effects in different settings (e.g., D. S. Blough, 1975; Hinson & Malone, 1980).

EXPERIMENT 2

Experiment 2 was designed to examine different dependent measures of stimulus control for comparison with the conventional response-rate measures used in maintained generalization gradients. To the extent possible, stimulus values and presentation frequencies comparable to Experiment 1 were used throughout Experiment 2. The discrimination tasks in Experiment 2 differed from the prior experiment in that two response alternatives were always available, instead of a single response. In addition, some conditions involved discrete-trial reinforcement rather than continuous-trial VI reinforcement.

METHOD

Subjects

Eight male homing pigeons served as subjects. Birds 10, 11, 12, 14, 15, and 16 were experimentally naive prior to this experiment, and Birds 9 and 13 had varied training histories, none of which included dimensional dis-

crimination learning. The subjects were maintained at 80% of their laboratory free-feeding weights.

Apparatus

Experiments were carried out in a standard Campden Instruments three-key operant conditioning chamber. The internal dimensions of the chamber were 35 cm by 35 cm by 33 cm. The center key was covered with black tape. The two side translucent pecking keys, 2.72 cm in diameter, were located 27.5 cm above the floor and 6 cm from either side of the chamber. A 6-W houselight provided diffuse illumination throughout the chamber during experimental sessions. A 5 cm by 6 cm aperture, 13.5 cm from the floor and in the middle of the front panel, provided access to a food magazine. Mixed grain presented for 4 s was used as a reinforcer. The experimental chamber was part of a larger sound-proofing box and contained a fan for ventilation and masking of extraneous noise. Experimental events and data collection were controlled by a microcomputer in an adjacent room.

Procedure

After preliminary autoshaping to both keys for naive and experienced birds, we exposed the subjects to three types of discrimination training. For all conditions, the stimuli were 24 flicker rates of an LED that were identical to those described in Experiment 1. Frequency of the stimuli varied from 4 to 27 Hz in equal 1-Hz intervals. An identical LED was mounted 2 cm behind each of the two side translucent pecking keys. A single session comprised 120 stimulus presentations. Each stimulus appeared five times during the session, but otherwise the sequence of stimuli was determined by a pseudorandom process that changed daily. In all three conditions, the subject was provided with two response alternatives.

Conditions of Experiment 2 involved different response and reinforcement parameters. One condition, referred to as *continuous*, was a two-alternative maintained generalization procedure. Right-key responses during the higher 12 flicker rates and left-key responses during the lower 12 flicker rates were reinforced according to a VI 60-s schedule. All other responses were extinguished. Duration of each stimulus presentation during the continuous condition was 30 s.

Fig. 3. Discrimination functions for the group of 8 birds in the continuous and discrete conditions of Experiment 2. Response rate to the right key (O) and left key (*) and the percentage of right-key responses as the first choice (+) are displayed. Each function represents the mean of the last five sessions of each condition. Flicker frequencies in Hz appear along the x axis. The vertical line between 15 and 16 Hz shows the division between stimuli associated with reinforcement from left- or right-key responses.

Another condition, referred to as *discrete*, was a two-alternative discrete-trial procedure. Right-key responses during the higher 12 flicker rates and left-key responses during the lower 12 flicker rates ended the trial with food reinforcement. A correction procedure was employed in that incorrect responses did not end the trial. Rather, the subject was required eventually to make the correct response that would then terminate the trial with food reinforcement. The stimuli remained on both keys until the trial was over. A 5-s intertrial interval (ITI) separated consecutive stimulus presentations.

The final condition, referred to as *discrete probabilistic*, was a variation of the two-alternative discrete procedure. In this condition, correct responses (as defined above for the discrete procedure) had a .5 probability of ending the trial in reinforcement and a .5 probability of ending the trial without reinforcement. In-

correct responses always ended the trial without reinforcement. As before, the stimuli remained on both keys until the trial was over, and a 5-s ITI was in effect.

The 8 subjects were placed in two groups and exposed to the discrete and continuous discrimination conditions in counterbalanced order. Group 1 comprised Birds 9, 10, 13, and 14, and Group 2 included Birds 11, 12, reinforcer rates 15, and 16. After the first two conditions, subjects were exposed to the discrete probabilistic procedure. The order of conditions and number of sessions for each condition was as follows: Group 1 received the discrete condition first, followed by the continuous and discrete probabilistic procedures. Each condition consisted of 32 sessions. Birds in Group 2 were exposed first to the continuous condition, followed by the discrete probabilistic conditions. These conditions each lasted for 32 sessions.

RESULTS AND DISCUSSION

As in Experiment 1, the results for individual subjects were similar during Experiment 2 despite some individual differences in the magnitude and form of responding. Two subjects showed a minor difference in performance from the others in one condition, and this will be discussed later. Otherwise, discrimination performance for all subjects was stable after 2 weeks and showed no systematic changes for the remainder of each condition. There were no obvious effects of order of exposure to the first two conditions of Experiment 2.

Figure 3 provides three discrimination functions for the 8 subjects, averaged over the last five sessions of the discrete and continuous conditions. The function with circle symbols shows mean response rate to the right key during the continuous procedure, and the function with asterisks shows mean response rate to the left key. The function with upright cross symbols represents the percentage of responses made first to the right key during the discrete condition, with the function for the left key being implied by symmetry.

In the continuous condition, there was good discrimination between left and right response alternatives. Response rate for each key was higher during stimuli from the half of the continuum providing VI reinforcement for that response. Rates during EXT stimuli for each key were lowest during extreme stimulus val-

ues. At the same time, prominent positive dimensional contrast effects appeared in gradients for left and right keys. The gradients show peaks at 7 Hz for the left key and 23 Hz for the right key. Group differences in responding between peak and extreme S+ values (i.e., 4 and 7 Hz for the left key or 23 and 27 Hz for the right key) were significant according to a one-way ANOVA, for both left-key responses, $F(1, 14) = 5.52, p < .05$, and right-key responses, $F(1, 14) = 14.4, p < .05$. The magnitude of dimensional contrast, based on the difference between responding during peak and extreme stimuli, is approximately 10% of peak responding for the left key and about 22% for the right key.

The right-key function for Experiment 2 can be compared to the function obtained in Experiment 1. Gradients for the two experiments show good agreement, with the most striking feature being the similar nonmonotonic form. And like the gradient from Experiment 1, there is no indication of negative dimensional contrast in either left- or right-key response rates in Figure 2, presumably for the reason given before. Yet, one can argue that inhibitory effects reflect competing responses (e.g., Hinson & Staddon, 1978; Staddon, 1983). On this interpretation, the positive function for the left key represents negative dimensional contrast for the right key. Although this suggestion is speculative, it is at least consistent with one theory of behavioral contrast.

Differences in overall response rates during Experiments 1 and 2 complicate detailed comparisons. However, relative gradient form, in which response rates are scaled in terms of the percentage of the maximum, seems to indicate that the magnitude of positive dimensional contrast was greater in Experiment 2. Also, response rate during EXT stimuli bordering VI stimuli was relatively higher in the single-key procedure, as was response rate during more extreme EXT stimuli. A one-way ANOVA based on difference scores for responding between peak and border VI stimuli and peak and extreme VI stimuli indicated that the difference between the two experiments in responding near the VI/EXT border was significant, $F(1, 14) = 10.64, p < .05$, but the difference in magnitude of dimensional contrast was not significant, $F(1, 14) = 2.67, p > .05$.

The function for the discrete condition in Figure 3 differs in important ways from the functions for the continuous condition. Instead of a nonmonotonic relation, the discrete function resembles the normal ogive observed in many psychophysical functions. For 2 of the 8 subjects, there was somewhat of a bias toward the right key. Therefore, the percentage of right-key responses at the lower end of the continuum was higher than the percentage of left-key responses at the higher end. Apart from this bias for 2 birds, the form of the function is reasonably symmetrical about the midpoint of the stimulus continuum. Absent from the discrimination function is any relative enhancement of the discrete-response measure near the border. That is, there is no indication of positive dimensional contrast.

The point of subjective equality (PSE), identified by a right-key response probability of .5, appears to be between 15 and 16 Hz. The difference limen (DL) above and below the midpoint of the stimulus continuum may be identified by the difference between the PSE and right-key response probabilities of .25 and .75. By this measure, the DL above and below the midpoint seems to be about equal. Finally, beyond approximately 4 Hz on either side of the border, there are no further improvements in discrimination. A one-way ANOVA reveals no significant differences in responding among the eight highest stimuli, $F(7, 56) = 0.201, p > .05$, or among the eight lowest stimuli, $F(7, 56) = 0.401, p > .05$.

Despite the fact that one function is monotonic and the other is nonmonotonic, the slopes of the discrete and continuous functions are quite similar near the left-right response border (i.e., between approximately 12 and 19 Hz). Clear differences appear only for more extreme values on either end of the continuum. In addition, the peak of each response-rate function occurs in a region of the continuum where essentially unchanged discrimination prevails, as indicated by the discrete-response measure. And, of course, the decreases in response rate at extreme values of the continuous functions also occur in a region of unchanged discrimination for the discrete function.

Figure 4 provides individual gradients for representative subject from each of the two groups in Experiment 2. The functions in Figure 4 are based on the last 10 sessions of the discrete and continuous discrimination con-

Fig. 4. Discrimination functions for representative birds from the continuous and discrete conditions of Experiment 2. Response rate to the right key (O) and left key (*) and percentage of right-key responses as the first choice (+) are displayed. Each function represents the mean of the last 10 sessions of each condition. Flicker frequencies in Hz appear along the x axis. The vertical line between 15 and 16 Hz shows the division between stimuli associated with reinforcement from left- or right-key responses.

ditions. Individual subjects differed in overall response rate and in relative rate to left and right keys. Although there is considerable variability in both the peaks of the functions and

the relative magnitude of dimensional contrast, all individual gradients for the continuous condition show a nonmonotonic form. Individual discrimination functions for the discrete con-

dition are sigmoidal in form. The continuous and discrete functions are most similar in the border region between VI and EXT stimuli and least similar at more extreme values. In each case, the peak in the right-key continuous gradient occurs beyond the point at which the discrete function indicates unchanging discrimination.

To amplify the comparison between continuous and discrete discrimination conditions, Figure 5 provides a different analysis of the continuous response-rate measure. This figure includes the percentage of right-key responses during the discrete condition, familiar from Figure 3. Also included in Figure 5 is the percentage of right-key responses relative to total responding for both keys during the continuous condition, represented by sideways cross symbols. When response rate is plotted in this fashion, the function takes on a sigmoidal shape. And with the exception of the slight right-key response bias of 2 birds in the discrete condition, the two discrimination functions in Figure 5 are very similar. The close agreement between these functions is not forced by the dependent measures.

Figure 6 provides a similar display for the representative subjects from Figure 4. Again there is fairly close agreement between the functions in Figure 6 for all birds, especially in the border region between VI and EXT values. Of course, the relative rate measure tends to obscure the dimensional contrast effect that is obvious in the absolute response-rate measure. For example, one can barely see the effect peeking through for Bird 10 in Figure 6 even though the contrast effect for this bird is huge in Figure 4. Nonetheless, this comparison shows how close the two estimates are, especially in assessing discrimination in the border region of VI and EXT where discrimination should be most difficult.

Figure 7 compares mean response rate, familiar from the continuous condition in Figure 3, with a discrete measure taken from the same data. In this case, the percentage of responses to the right key made as the first choice appears along with the mean response-rate gradients. This plot is comparable to the function for the discrete condition in Figure 3 and yields a similar sigmoidal function. Note that this first-response function appears in the same trials in which response rates are enhanced at stimulus values an intermediate distance from the

Fig. 5. Discrimination functions for the group of 8 birds in Experiment 2. Mean percentage of first responses to the right key (+) and mean percentage of right-key response rate (X) are displayed. Functions represent the last five sessions of the continuous and discrete conditions. Flicker frequencies in Hz appear along the x axis. The vertical line between 15 and 16 Hz shows the division between stimuli associated with reinforcement from left- or right-key responses.

border. Although not identical, the first choice profile is very similar to the discrete-choice function.

Data from representative individual subjects appear in Figure 8. For 3 of the 4 birds, slopes of the first-response and total-response functions are extremely similar near the border of VI and EXT stimuli. And, again, the first-response function appears to be sigmoidal. All of the left-key peaks are beyond the point at which the first-response measure does not significantly change. But the peaks of the right-key gradients for Birds 10 and 11 are not clearly beyond the upper inflection of the first-response function. Further, there is even a hint of a downturn in the first-response function for Bird 10 at the most extreme stimulus. There is no similar indication in data from any other subject.

Finally, Figure 9 provides results from the discrete probabilistic discrimination condition.

Fig. 6. Discrimination functions for individual birds in Experiment 2. Mean percentage of first responses to the right key (+) and mean percentage of right-key response rate (X) are displayed. Functions represent the last 10 sessions of the continuous and discrete conditions. Flicker frequencies in Hz appear along the x axis. The vertical line between 15 and 16 Hz shows the division between stimuli associated with reinforcement from left- or right-key responses.

This figure shows the percentage of first responses to the right key, which is comparable to earlier discrete measures. Once again, the discrimination function is sigmoidal. More-

over, by this final stage of training, the bias toward the right key, which earlier occurred for 2 subjects, had practically disappeared. In all important respects, the discrimination func-

tion for the discrete probabilistic condition is highly similar to the discrete-response functions of Figures 3 and 5. As before, a one-way ANOVA reveals no significant differences in responding among the eight lowest stimulus values, $F(7, 56) = 0.25$, $p > .05$, or among the eight highest stimulus values, $F(7, 56) = 1.39$, $p > .05$. Individual data in Figure 10 show a little more variability in responding in the discrete probabilistic condition when compared to the discrete condition, but the discrimination profile is similar.

GENERAL DISCUSSION

Before considering the general implications of these studies, it is convenient to summarize. Experiments 1 and 2 examined dimensional stimulus control among a standard set of flicker-rate values using one- and two-response alternative tasks. Positive dimensional contrast was readily obtained with either single or dual response alternatives in a free-operant task. Both the form of maintained gradients and the magnitude of dimensional contrast were comparable in the one- or two-response tasks, despite some differences in relative responding during EXT stimuli. This result is similar to studies that have found two-way peak shift effects when two response alternatives are offered (D. S. Blough, 1973).

In discrete-trials conditions, there was no indication of dimensional contrast. Instead, alternative response probability varied monotonically with stimulus value producing a function reminiscent of the normal ogive characteristic of many psychophysical discrimination tasks (e.g., Heinemann et al., 1969). Reducing payoff probability in the discrete procedure did not markedly affect discrimination functions.

Finally, additional indices of discrimination during the two-alternative continuous condition, such as the percentage of first responses to the right key or percentage of right-key responses among total response rate, agreed closely with discrimination measures taken from the discrete and discrete probabilistic conditions. All discrimination functions had similar slopes in the border region between S+ and S- regardless of whether the measure also showed positive dimensional contrast.

What do these results reveal about dimen-

Fig. 7. Discrimination functions for the group of 8 birds in the continuous condition of Experiment 2. Response rate to the right key (O) and left key (*) and the percentage of right-key responses as the first choice (+) are displayed. Each function represents the mean of the last five sessions. Flicker frequencies in Hz appear along the x axis. The vertical line between 15 and 16 Hz shows the division between stimuli associated with reinforcement from left- or right-key responses.

sional contrast and dimensional stimulus control? On first inspection, dimensional contrast effects seem to indicate that there is no direct relationship between stimulus difference and discrimination (e.g., D. S. Blough, 1983). This implausible suggestion is inconsistent with several aspects of the current results. For instance, indices of discrimination based on discrete measures produced the expected monotonic relation between stimulus difference and discrimination. Such outcomes are consistent with the predictions of traditional conditioning models like those based on Spence's (1937) interacting gradient notion and more recent models based on the theory of signal detectability (e.g., Boneau & Cole, 1967; Heinemann & Chase, 1975).

Compatible with the discrete-response analysis is the view that response rate is an impure measure of discrimination that is influenced

Fig. 8. Discrimination functions for individual birds in the continuous condition of Experiment 2. Response rate to the right key (O) and left key (*) and the percentage of right-key responses as the first choice (+) are displayed. Each function represents the mean of the last 10 sessions. Flicker frequencies in Hz appear along the x axis. The vertical line between 15 and 16 Hz shows the division between stimuli associated with reinforcement from left- or right-key responses.

by variables not directly related to discriminative control (e.g., D. S. Blough, 1965, 1969; White, Pipe, & McLean, 1984; see also Honig & Urcuioli, 1981). It is easy to argue that

discrete measures, which are less subject to contaminating influences, should replace free-operant measures of stimulus control. But this position does not answer the original question

of why response-rate differences should exist among stimuli that signal equal frequencies of reinforcement. Moreover, it ignores the fact that response rates are extremely orderly under a variety of conditions.

The present studies indicate that response rate can be as informative as discrete choice. For example, estimates of discrimination between bordering S- and S+ stimuli in Experiment 2 were quite similar for continuous and discrete measures. This similarity extended to both absolute (e.g., Figure 3) and relative (e.g., Figure 5) response rates. It was clearly important to remove the asymmetry in payoffs for responding and not responding inherent in the single-alternative procedure. For example, response rate was a less sensitive index of discrimination when only one response alternative was available, indicated by the slope of the maintained gradient along the border of S+ and S-. Otherwise, the continuous response measure provided an equally informative description of discrimination compared to the discrete measure.

But beyond this, response rate was seemingly sensitive enough to reveal additional discriminative processes that escaped the simple discrete measure. Specifically, dimensional contrast effects that would have gone unnoticed in the discrete measures were evident in response rates. What discriminative processes might be responsible for dimensional contrast? One interpretation that would remove some of the mystery from dimensional contrast is that response-rate differences reflect not only discrimination between S+ and S-, but also discrimination within the sets of S+ and S- stimuli. That is, the ordering of response rates among S- and S+ may reflect organization of stimuli within each stimulus class, as well as discriminability from other stimulus classes. Thus, the apparent nonmonotonic relation between similarity of stimuli and response-rate discrimination measures would no longer be troublesome.

Hinson and Higa (in press) discuss the notion that dimensional contrast effects could reflect some sort of relational categorization of stimuli within the range of values actually presented. Using the example of positive dimensional contrast, peak response rates might occur during the most typical or average S+ value, perhaps determined by both the range and frequency of presentation of all S+ values.

Fig. 9. Discrimination functions for the group of 8 birds in Experiment 2. Mean percentage of first responses to the right key for the discrete probabilistic condition is displayed. Functions represent the last five sessions of the condition. Flicker frequencies in Hz appear along the x axis. The vertical line between 15 and 16 Hz shows the division between stimuli associated with reinforcement from left- or right-key responses.

According to this argument, the peak S+ value would not be the most discriminable from S- but one intermediate within the range of variation of the S+ set. This is exactly the result obtained in Experiments 1 and 2.

Such an interpretation is similar to the central-tendency account of human stimulus generalization (e.g., Thomas & Jones, 1962; Thomas, Strub, & Dickson, 1974). Several studies have shown that the peak of generalization gradients obtained during extinction tests depends on the distribution of test stimuli rather than the difference between training and test stimuli along the physical dimension. Stimuli appear to be judged according to a relational category organization consistent with adaptation level theory (see also Thomas, Windell, Williams, & White, 1985).

Although the central-tendency explanation is consistent with some aspects of the present results, there are difficulties in its application to dimensional contrast (see Hinson & Higa,

Fig. 10. Discrimination functions for individual birds in Experiment 2. Mean percentage of first responses to the right key for the discrete probabilistic condition is displayed. Functions represent the last 10 sessions of the condition. Flicker frequencies in Hz appear along the x axis. The vertical line between 15 and 16 Hz shows the division between stimuli associated with reinforcement from left- or right-key responses.

in press). Apart from differences in procedures and subjects, the central-tendency notion does not readily explain bimodal postdiscrimination gradients obtained with multiple-stimulus training in either human (e.g., White &

Thomas, 1979) or animal studies (e.g., Kalish & Guttman, 1959). Bimodal discrimination gradients, as well as failures of predicted summation effects, have also been a continuing problem for Spence's (1937) gradient-sum-

mation approach (e.g., D. S. Blough, 1983; Kalish & Guttman, 1959).

Despite potential problems, Hinson and Higa (in press) note that the central-tendency explanation is an easily testable approach. For example, they suggest an adequate test would be provided by analysis of a discrimination involving a set of S+ stimuli bounded on both ends of a continuum by S-. With a uniform stimulus continuum, a single peak in S+ responding between the S- boundaries is predicted by the central-tendency account. On the other hand, dual peaks in S+ responding at the S- borders would rule out central tendency as an explanation. Regardless of the outcome of this experiment, the further analysis of variables controlling similarity within S- and S+ stimulus classes should help to explain dimensional contrast.

REFERENCES

- Blough, D. S. (1965). Definition and measurement in generalization research. In D. I. Mostofsky (Ed.), *Stimulus generalization* (pp. 30-37). Stanford, CA: Stanford University Press.
- Blough, D. S. (1969). Generalization gradient shape and summation in steady-state tests. *Journal of the Experimental Analysis of Behavior*, **12**, 91-104.
- Blough, D. S. (1973). Two-way generalization peak shift after two-key training in the pigeon. *Animal Learning & Behavior*, **1**, 171-174.
- Blough, D. S. (1975). Steady state data and a quantitative model of operant generalization and discrimination. *Journal of Experimental Psychology: Animal Behavior Processes*, **1**, 3-21.
- Blough, D. S. (1983). Alternative accounts of dimensional stimulus control. In M. L. Commons, R. J. Herrnstein, & A. R. Wagner (Eds.), *Quantitative analyses of behavior: Vol. 4. Discrimination processes* (pp. 59-72). Cambridge, MA: Ballinger.
- Blough, P. M. (1972). Wavelength generalization and discrimination in the pigeon. *Perception & Psychophysics*, **12**, 342-348.
- Blough, P. M., & Blough, D. S. (1985). Sequential effects in dimensional contrast. *Journal of the Experimental Analysis of Behavior*, **44**, 233-244.
- Boneau, C. A., & Cole, J. L. (1967). Decision theory, the pigeon, and the psychophysical function. *Psychological Review*, **74**, 123-135.
- Catania, A. C., & Gill, C. A. (1964). Inhibition and behavioral contrast. *Psychonomic Science*, **1**, 257-258.
- Chase, S. (1983). Pigeons and the magical number seven. In M. L. Commons, R. J. Herrnstein, & A. R. Wagner (Eds.), *Quantitative analyses of behavior: Vol. 4. Discrimination processes* (pp. 37-57). Cambridge, MA: Ballinger.
- Farthing, G. W. (1974). Behavioral contrast with multiple positive and negative stimuli on a continuum. *Journal of the Experimental Analysis of Behavior*, **22**, 419-425.
- Graf, V. (1973). De Lange characteristics for the freshwater turtle *Chrysemys picta picta*, and the pigeon *Columba livia*. *Vision Research*, **13**, 1815-1822.
- Guttman, N., & Kalish, H. I. (1956). Discriminability and stimulus generalization. *Journal of Experimental Psychology*, **51**, 79-88.
- Hanson, H. M. (1959). Effects of discrimination training on stimulus generalization. *Journal of Experimental Psychology*, **58**, 321-334.
- Heinemann, E. G., Avin, E., Sullivan, M. A., & Chase, S. (1969). Analysis of stimulus generalization with a psychophysical method. *Journal of Experimental Psychology*, **80**, 215-224.
- Heinemann, E. G., & Chase, S. (1975). Stimulus generalization. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes: Vol. 2. Conditioning and behavior theory* (pp. 305-349). Hillsdale, NJ: Erlbaum.
- Hinson, J. M. (1988). Absolute and relative measures of dimensional contrast. *Journal of the Experimental Analysis of Behavior*, **50**, 249-260.
- Hinson, J. M., & Higa, J. J. (in press). Stimulus variation and dimensional contrast. *Animal Learning & Behavior*.
- Hinson, J. M., & Lockhead, G. R. (1986). Range effects in successive discrimination. *Journal of Experimental Psychology: Animal Behavior Processes*, **12**, 270-276.
- Hinson, J. M., & Malone, J. C., Jr. (1980). Local contrast and maintained generalization. *Journal of the Experimental Analysis of Behavior*, **34**, 263-272.
- Hinson, J. M., & Staddon, J. E. R. (1978). Behavioral competition: A mechanism for schedule interactions. *Science*, **202**, 432-434.
- Honig, W. K., & Urciuoli, P. J. (1981). The legacy of Guttman and Kalish (1956): 25 years of research on stimulus generalization. *Journal of the Experimental Analysis of Behavior*, **236**, 405-445.
- Kalish, H. I., & Guttman, N. (1959). Stimulus generalization after training on three stimuli: A test of the summation hypothesis. *Journal of Experimental Psychology*, **57**, 268-272.
- Malone, J. C., Jr. (1974). The effect of number of stimuli on the steady-state generalization gradient: A test of the summation hypothesis. *Journal of Experimental Psychology*, **102**, 729-732.
- Malone, J. C., Jr. (1975). Stimulus-specific contrast effects during operant discrimination learning. *Journal of the Experimental Analysis of Behavior*, **24**, 281-289.
- Malone, J. C., Jr., & Staddon, J. E. R. (1973). Contrast effects in maintained generalization gradients. *Journal of the Experimental Analysis of Behavior*, **19**, 167-179.
- Nevin, J. A. (1984). Quantitative analysis. *Journal of the Experimental Analysis of Behavior*, **42**, 421-434.
- Reynolds, G. S. (1961). Contrast, generalization, and the process of discrimination. *Journal of the Experimental Analysis of Behavior*, **4**, 289-294.
- Spence, K. W. (1937). The differential response in animals to stimuli varying within a single dimension. *Psychological Review*, **44**, 430-444.
- Staddon, J. E. R. (1983). *Adaptive behavior and learning*. Cambridge: Cambridge University Press.
- Thomas, D. R., & Jones, C. G. (1962). Stimulus generalization as a function of the frame of reference. *Journal of Experimental Psychology*, **64**, 77-80.
- Thomas, D. R., Strub, H., & Dickson, J. F., Jr. (1974).

- Adaptation level and the central tendency effect in stimulus generalization. *Journal of Experimental Psychology*, **103**, 466-474.
- Thomas, D. R., Windell, B. T., Williams, J. L., & White, K. G. (1985). Stimulus presentation frequency in brightness discrimination and generalization: A test of adaptation-level and signal-detection interpretations. *Perception & Psychophysics*, **37**, 243-248.
- White, K. G., Pipe, M.-E., & McLean, A. P. (1984). Stimulus and reinforcer relativity in multiple schedules: Local and dimensional effects on sensitivity to reinforcement. *Journal of the Experimental Analysis of Behavior*, **41**, 69-81.
- White, K. G., & Thomas, D. R. (1979). Postdiscrimination stimulus generalization in humans: An extension of Galizio and Baron. *Animal Learning & Behavior*, **7**, 564-565.

Received June 13, 1988

Final acceptance October 7, 1988