

*THE QUANTAL NATURE OF CONTROLLING STIMULUS-RESPONSE RELATIONS AS MEASURED IN TESTS OF STIMULUS GENERALIZATION<sup>1</sup>*

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This paper is a selective review of research that addresses the validity of two interpretations of stimulus generalization. One interpretation, referred to as the descriptive stimulus-control interpretation, proposes that during stimulus generalization a continuous relation exists between stimulus and response dimensions. The other interpretation, referred to as the quantal interpretation, proposes that a stimulus-response relation functions as a unit that may or may not occur. From the latter viewpoint, the continuity typically obtained during generalization tests is deemed to be artifactual and to result from averaging across multiple controlling stimulus-response relations. Studies examining the contribution of these multiple relations to generalization gradients are reviewed. With few exceptions, the quantal interpretation appears to better characterize the results of these studies. Implications for peak shift, selection of analytical level, and identification of the behavioral unit are discussed, as well as factors that may determine the acceptability of the quantal interpretation.

*Key words:* stimulus generalization, generalization gradients, quantal interpretation, descriptive stimulus-control interpretation, stimulus control

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## INTRODUCTION

"It must be assumed that some physical quantities so far regarded as continuous are composed of elementary quanta" (Einstein & Infeld, 1938, p. 251). This statement by Einstein and Infeld represented a fundamental departure in the manner in which quantities were conceptualized in physics. Prior to this conceptual departure, physical quantities were regarded to be of a continuous nature. Quantum physics, however, provided another view in which physical quantities were found to be multiples of a definite unit. Similarly, the behavioral phenomenon of stimulus generalization has also been assumed to be a continuous process (Guttman & Kalish, 1956; Hull, 1947; Pavlov, 1927), but during the past two decades a body of literature has accumulated supporting the view that the continuous functions observed in generalization gradients are artifactual and that stimulus-controlled behavior is a quantal entity.

*Stimulus Generalization: Two Interpretations*

Since the 1956 report by Guttman and Kalish, a vast data base has been compiled on the variables that affect generalization gradients (cf. Hearst, Besley, & Farthing, 1970; Mackintosh, 1977; Rilling, 1977; Terrace, 1966). Along with this empirical work, a conceptual interpretation of stimulus generalization developed with certain assumptions. These assumptions were widely held, implicit in several theories of stimulus generalization

(e.g., Hull, 1947; Kalish, 1969), and for the purpose of this paper will be termed the descriptive stimulus-control interpretation (Sidman, 1969).

Central to this interpretation are the following four assumptions: (1) A continuous relation exists between the dimension of the training stimulus and the measured behavior (e.g., Nevin, 1973, p. 117; Terrace, 1966, p. 271; cf. Stoddard & Sidman, 1971a); that is, the stimulus and response dimensions vary together in a continuous fashion. (2) Given a continuous relation between the stimulus and response, varying the experimenter-specified dimension of the training stimulus will result in corresponding changes in the measured behavior (Honig & Urcuioli, 1981, p. 409; Stoddard & Sidman, 1971a); that is, response number, rate, or strength will diminish as the test stimulus diverges from the training stimulus. (3) Gradients are a measure of the controlling stimulus-response relation specified by the experimenter (e.g., Rilling, 1977; Terrace, 1966). For instance, after a line-tilt discrimination is trained, responses to subsequent tests of various line tilts will exhibit only the control established via training. No stimulus other than the line tilt will come to control behavior unless it is specifically trained. (4) The same stimulus controls responding both before and after changes occur in the area, shape, or slope of a gradient. For example, the flattening of a gradient after extended testing is interpreted as a decrease in the differential control exerted by the training stimulus. The same controlling stimulus resulted in both the earlier peaked and the latter flattened gradients. The change in gradient form is due only to a change in degree or extent of control by those stimuli.

On the basis of these assumptions, three typical gradient forms may be interpreted. (1) A peaked sharp gradient would indicate that the training stimulus exercises strong differential control relative to the test stimuli (Sidman, 1969; e.g., Terrace, 1966). (2) The so-called "flat" gradient would be interpreted as indicating either an approximation of complete generalization or the absence of stimulus control by the experimenter-specified stimulus (Rilling, 1977). (3) An intermediate gradient

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indicates that the training stimuli and test stimuli exert control, but the degree of control diminishes as the test stimuli diverge from the value of the training stimulus.

In addition to the descriptive stimulus-control interpretation, there is an alternative view, developed through the work of several investigators (e.g., Cumming & Eckerman, 1965; Migler, 1964; Ray, 1981; Ray & Sidman, 1970; Sidman, 1969, 1977, 1980; Stoddard & Sidman, 1971a, 1971b), that will be referred to as the quantal interpretation (Rilling, 1977). The term "quantal," as it will be used here, refers to the measurement of a quantity that is always a multiple of a definite unit (*International Dictionary*, 1956). The notion of quanta is illustrated in the following example taken from Einstein and Infeld (1938, p. 250): While the output of a coal mine can vary in a continuous fashion, the number of miners cannot. The number of miners must always increase by a multiple of one. Miners and, of course, the supraordinate class of humans are quantal entities.

Paramount to the quantal interpretation is the assumption "that behavior is never undetermined, that all responses are controlled, if not by stimuli the experimenter has specified, then by others. Control may fluctuate from trial to trial so that it is difficult to measure, but this is not the same as random responding" (Sidman, 1980, p. 286). If this assumption is accepted, then what are usually called chance responding, variations in the degree or extent of control, or the absence or loss of control must in fact refer to the control of behavior (perhaps unmeasured) by stimuli not specified by the experimenter. If, however, the above assumption is not accepted, then phrases like those above may lead to equating the absence of control by an experimenter-specified stimulus with the absence of any controlling stimulus. Holding the assumption that there is always a controlling stimulus for behavior has had utility by leading to further analyses that subsequently revealed previously unidentified controlling stimuli (e.g., Bickel, Stella, & Etzel, 1984; Cumming & Berryman, 1965, pp. 322-328).

The second assumption of the quantal interpretation follows from the first; namely, a

controlling stimulus-response relation is an integral unit (Ray, 1969; cf. Sidman, 1980). As such, the measure of the unit at any instant can either be one, the occurrence of the unit, or zero, the nonoccurrence of the unit. The occurrence of the controlling stimulus-response relation requires that the experimenter-specified stimulus, or one perfectly correlated with it, be a member of the class of stimuli that comprise the controlling stimulus-response relation. The nonoccurrence of the unit results from either the experimenter-specified stimulus or some other concurrently available stimulus controlling unmeasured behavior. Consequently, any summary measure of a controlling stimulus-response relation in which unity (or disunity) between stimulus presentations and the occurrence (or nonoccurrence) of the behavioral unit is not obtained must result from averaging several occurrences of the measured behavior with several occurrences of some other controlling stimulus-response relation (Ray & Sidman, 1970; Sidman, 1980). Thus, the quantal interpretation suggests that a multiplicity of stimuli in experimental environments may acquire controlling properties and may be inadvertently measured along with the control exerted by the experimenter-specified stimulus (Ray & Sidman, 1970; Sidman, 1969). This possibility was cogently noted by Prokasy and Hall (1963) when they stated:

What represents an important dimension of the physical event for the experimenter may not even exist as part of the effective stimulus for the subject. Similarly, the subject may perceive aspects of an experimenter event which have been ignored by, or are unknown to, the experimenter. (p. 315)

Based upon the above assumptions, the following inferences can be made, specifying the contributions of different stimulus-response relations to the three typical generalization forms: (1) A sharp and peaked gradient results from the experimenter-specified stimulus (or one perfectly correlated with it) functioning as the controlling stimulus for the measured behavior (Sidman, 1969). (2) A flat gradient results from the experimenter-specified stim-

ulus exerting control over unmeasured behavior and/or a concurrently available stimulus other than that specified by the experimenter exerting control over measured and/or unmeasured behavior (Sidman, 1969). (3) An intermediate gradient results from averaging measures of two or more controlling stimulus-response relations. The relations that may contribute to the intermediate gradient are the experimenter-specified stimulus exerting control over measured behavior, control over unmeasured behavior by the experimenter-specified stimulus, and/or control over unmeasured or measured behavior by a stimulus not specified by the coordinates of the generalization gradients (Rand, 1977; Ray & Sidman, 1970; Stoddard & Sidman, 1971b). Thus, an intermediate gradient would result from the co-presence of control that would separately result in the peaked and flat gradients.

Research relevant to the quantal interpretation has not been discussed in the many reviews of stimulus generalization cited above, with the exception of brief discussions by Nevin (1973) and Rilling (1977). The purpose of the present paper is to review stimulus-generalization research that addresses the empirical validity of the quantal interpretation. This review is focused primarily on those studies that have conducted microanalyses of the contribution of multiple controlling relations to stimulus generalization. These studies can be organized into three areas: (1) studies that have examined the contributions of *multiple controlling stimulus-response relations* in the analysis of stimulus generalization by conducting generalization tests after training two or more responses to two or more points along a stimulus dimension; (2) studies in which tests of stimulus generalization were conducted to assess *the existence of other controlling relations* that were not specified by the experimenter; (3) studies that employed *microanalyses of response rate* during generalization tests. After the studies from each of these areas are reviewed, the quantal and descriptive stimulus-control interpretations are evaluated and their implications are discussed.

## MICROANALYSIS I: MULTIPLE CONTROLLING STIMULUS-RESPONSE RELATIONS

The power of an experimental analysis resides in the direct manipulation of variables and the quantitative analyses of the effects of those variables on a phenomenon of interest. The most direct way to ascertain the contribution of multiple controlling stimulus-response relations in the analysis of stimulus generalization is to establish and measure those relations explicitly. In the research reviewed in this section, two or more responses from a single response dimension were trained to distinct and distant points along a single stimulus dimension. When this is done, the subsequent presentation of stimuli intermediate between the training values during tests of generalization should reveal whether continuous changes occur in behavior, or whether varying proportions of discrete controlling stimulus-response relations occur. The studies are reviewed according to the response dimension employed, including (1) spatial dimensions, (2) temporal dimensions, (3) dimensions engendered by schedules of reinforcement, and (4) dimensions of fundamental acoustical frequency.

### *Responses Along a Spatial Dimension*

Several studies have investigated the contributions of multiple controlling stimulus-response relations to the analysis of stimulus generalization by training responses along a spatial dimension. Cumming and Eckerman (1965), for example, trained 2 pigeons to peck two distant points along a 10-inch strip in the presence of particular levels of illumination. When the illumination was bright (1.1 log ft L, i.e., 3.77 log cd/m<sup>2</sup>), pecks that occurred between 1.5 and 2.5 inches from the left end of the strip were reinforced on a variable-interval (VI) schedule of reinforcement. When the strip was illuminated at a lower level (0.1 log ft L, i.e., 0.35 log cd/m<sup>2</sup>), pecks that occurred between 7.5 and 8.5 inches from the left end of the response strip were reinforced according to the same VI schedule. After 10 training sessions, a generalization test presented both training values as well as three intermediate

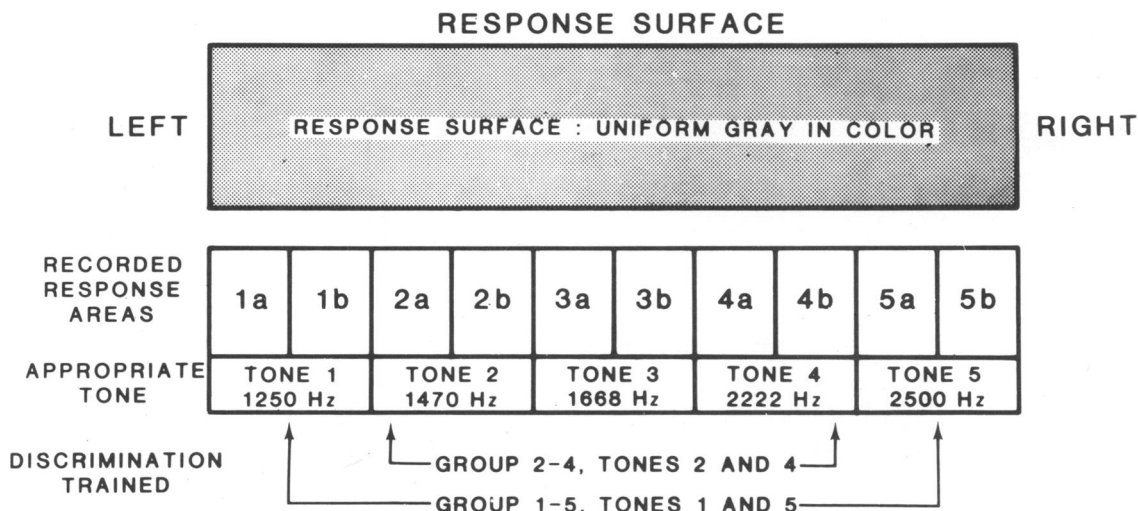


Fig. 1. Schematic representation of the response surface with the locations of discrimination for each group. Areas correlated with reinforcement during a particular training tone are indicated by the arrows (adapted from Wildemann & Holland, 1972, p. 421).

stimuli (1.03, 2.06, 2.74 log cd/m<sup>2</sup>). The distributions of responses obtained during the generalization test were bimodal and the majority of responses made during presentation of the test stimuli were at the locations reinforced during training trials. As the intermediate stimuli approached the value of one of the training stimuli, the proportion of responses made within the range of response locations correlated with that training stimulus increased. Stimuli equidistant from the two training stimuli resulted in equal proportions of responses made at the two reinforced locations. Thus, the proportion of responses made at each of the reinforced locations appeared to be dependent on the value of the test stimulus. Responses at intermediate unreinforced locations were less than 5% of the total test responses during the presentation of intermediate stimuli.

Cumming and Eckerman's (1965) study demonstrated that response location did not change continuously with the presentation of intermediate stimuli, as would be predicted from the descriptive stimulus-control interpretation. Instead, they obtained results consistent with the quantal interpretation, showing that the presentation of intermediate stimuli resulted in varying proportions of previously trained behavior. Also, they found that the

same test stimulus would, on some occasions, control responses at the left location, and at other times control responses at the right location.

An interesting extension of the Cumming and Eckerman study (1965) was conducted by Wildemann and Holland (1972). They investigated the effects of reinforcing responses that occurred at several points along a spatial dimension in the presence of different tones on the distribution of responses obtained during subsequent tests of stimulus generalization. Figure 1 presents the discriminations that were trained, and the stimuli and response positions that were utilized. Three groups of pigeons were trained using discrete-trial procedures. Only two groups will be discussed here, because similar results were obtained with the third group. In the first group, responses were reinforced only if they were located between 0 and 2 inches (response position one) and between 8 and 10 inches (response position five) from the left side of a 10-inch response strip, in the presence of a 1250-Hz (tone one) and a 2500-Hz (tone five) pure tone, respectively. In the second group, responses were reinforced only if they were located between 2 and 4 inches (response position two) and between 6 and 8 inches (response position four) from the left, in the presence of a 1470-Hz (tone two)

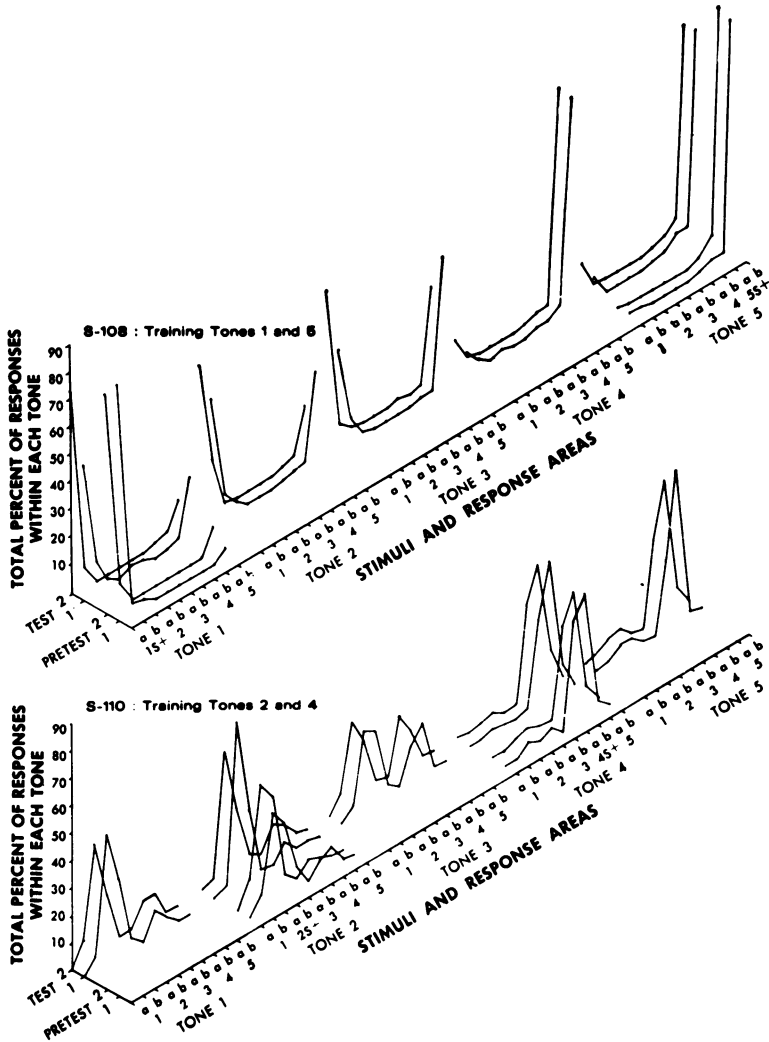


Fig. 2. Test response distributions in blocks of four sessions for S-108 trained on tones one and five and S-110 trained on tones two and four. Reinforcement areas are labeled S+. Pretest blocks 1 and 2 show the last eight sessions of discrimination training. Test blocks 1 and 2 show the response distributions during both training and test tones in the eight test sessions (from Wildemann & Holland, 1972, p. 430).

and 2222-Hz (tone four) pure tone, respectively.

Figure 2 shows the distribution of responses obtained from representative subjects in the two groups, during the last eight sessions of training and the eight sessions of testing. The training data are presented as the pretest blocks in the foremost plots, and the test data are in the midmost plots of Figure 2. Response distributions during both the training and the test tones are shown separately. For Subjects 108 and 110, the discrimination training resulted in response distributions that were

appropriate to the contingencies and correlated stimulus conditions. However, in the presence of each training stimulus, some responses were made that were appropriate to the other training stimulus. Few responses were made at positions that had never been correlated with reinforcement.

During the generalization test, presentation of the stimuli intermediate between the training values resulted in responses at only those positions previously correlated with reinforcement. For both subjects the proportion of responses made at each position correlated with rein-

forcement appeared to depend upon the proximity of the value of the training and test stimuli; for example, for Subject 108 tone four evoked substantially more responses at position five than at position one. Few responses occurred at intermediate positions. In discussing this point, the words of Prokasy and Hall (1963) were echoed by Wildemann and Holland when they stated, "subjects . . . responded during test tones as if key areas intermediate to those trained did not exist" (1972, p. 432). Moreover, Wildemann and Holland replicated Cumming and Eckerman's (1965) finding that the same stimulus may control responses at more than one location.

Similar findings were obtained by Gollub (1966), who trained 2 rats to interrupt with their noses one of eight photocell beams equally spaced in a 10-inch response slot. The rats' responses were reinforced on a VR-3 schedule of reinforcement. In the presence of a click occurring at 1.7 clicks per second (cps), responses interrupting the second photocell beam from the left side were reinforced. Reinforcement was also delivered in the presence of a 24.4-cps stimulus contingent upon the interruption of the seventh photocell beam from the left side. Discrimination training resulted in responses being confined primarily to the reinforced locations. In addition, Gollub, like Wildemann and Holland (1972), found that during discrimination training, some responses occurred at each of the reinforced locations in the presence of the training stimulus that was not correlated with that response location. The generalization tests conducted in extinction showed that the presentation of intermediate stimuli resulted in a bimodal distribution of responding in which responses occurred primarily at those locations previously correlated with reinforcement.

One study that employed a spatial response dimension reported finding a continuous relation between responding and the stimuli presented during generalization tests (Herrnstein & van Sommers, 1962). However, only the mean response locations obtained during generalization tests were presented, thereby making it impossible to ascertain whether the obtained continuity was due to providing a mea-

sure of central tendency that might average together different controlling relations or whether the continuity represented the moment-to-moment behavior of the subjects.

Thus, three of the four studies employing a spatial response dimension obtained data demonstrating that a continuous relation does not exist between response location and the stimuli presented during tests of stimulus generalization. Also, intermediate test stimuli were found in some instances to occasion responses at one previously reinforced location and sometimes to occasion responses at another reinforced location. This finding suggests that the same stimulus entered into more than one controlling stimulus-response relation. This observation is not necessarily unusual, for many stimuli have been found to enter into more than one relation, depending upon the context of their presentation (i.e., conditional discriminations). In the above generalization studies, however, the momentary conditions determining which relation a particular stimulus will enter are unknown.

The above argument needs to be qualified in one respect. For most subjects in the Wildemann and Holland (1972) and Gollub (1966) studies, the observation that test stimuli would enter more than one relation is not surprising inasmuch as training stimuli would occasion some responses at reinforced locations other than the response location specifically trained to that stimulus during baseline conditions. Thus, the training procedures may not have generated topographically distinct controlling stimulus-response relations. The extent to which the topographies overlapped may determine the strength of the conclusions that may be drawn from these studies. The strongest conclusions may be drawn from Cumming and Eckerman (1965) and from Subject S-108 of Wildemann and Holland's (1972) study; in both studies topographically distinct and mutually exclusive controlling stimulus-response relations were established.

#### *Responses Along a Temporal Dimension*

The research reviewed in this section examined the contributions of multiple controlling stimulus-response relations to the measure-

ment of stimulus generalization by employing responses from different points along a temporal dimension. Crowley (1979) differentially reinforced responses of specific durations in the presence of several levels of illumination. In the presence of one intensity level, responses with durations greater than 1 s but not exceeding 1.5 s were reinforced on a VI 20-s schedule. In the presence of a second intensity level, responses with a duration greater than 4 s but not exceeding 5 s were reinforced on an identical VI 20-s schedule. One group of rats was trained at both duration values; another group was trained with only the longer duration value. The stimuli (10 and 300  $\text{cd/m}^2$ ) correlated with a particular response duration were counterbalanced across subjects. When responding stabilized, stimulus-generalization tests were conducted under conditions of extinction between the 15th and 48th minutes of a 60-min session. Tests consisted of 1-min presentations of the test stimuli (10, 27, 60, 135, and 300  $\text{cd/m}^2$ ). Prior to and after the test period, the VI 20-s schedule and the correlated training stimuli were in effect.

Overall, the discrimination training resulted in distributions of response durations appropriate to the contingencies and correlated stimulus conditions. Some subjects trained to respond with two different durations exhibited overlapping response distributions, making interpretation of their generalization data difficult. Despite these individual differences, the data from the subjects that exhibited nonoverlapping baselines indicate that a continuous stimulus-generalization gradient would inadequately describe the relation between response duration and the stimuli presented. The subjects emitted various proportions of previously trained response durations. Across both groups, time spent responding decreased as the stimulus condition diverged from the training stimuli. As the time allocated to a response of one duration decreased, there was a concomitant increase in the time allocated to responses of the other duration. The group of subjects trained to respond with only one duration exhibited a similar decrement in the time allocated to the trained response during generalization tests. Unfortunately, measures were

not taken, for these subjects, of the responses to which time was allocated as the time spent engaging in the trained response decreased. The value of the Crowley study is that it obtained the same result irrespective of whether one or two stimulus-response relations were trained. This study, then, supported the quantal interpretation even when utilizing the procedure of explicitly training only one response, which approximates those typically used in stimulus-generalization research.

In addition to response duration, interresponse time (IRT) has also been used to analyze the contributions of multiple controlling relations. Migler (1964) employed a differential-reinforcement-of-low-rate (DRL) schedule, in which reinforcement is contingent upon responses that occur at least  $t$  s after the immediately preceding responses (Kramer & Rilling, 1970). Any IRT that does not equal or exceed  $t$  s resets the timing contingencies.

Specifically, Migler (1964) used a two-key DRL schedule (e.g., Nevin & Berryman, 1963) in which responses on Key A illuminated Key B. A response on Key B was reinforced if the interval between the responses exceeded a specified duration. In the presence of a click frequency of 2.5 cps (Stimulus 1), responses were reinforced if the interval between responses exceeded 6 s. In the presence of a click frequency of 45.8 cps, responses were reinforced if the interval between responses exceeded 0 s. After 45 sessions of discrimination training, reinforcement density was decreased to a probability of .5 so as to minimize the effects of extinction during the generalization test trials. During the generalization tests, six stimuli intermediate between the training stimuli were presented (i.e., 3.8, 5.6, 8.4, 12.7, 19.5, and 32 cps). Test trials were interpolated with training trials. Only one stimulus value was tested per session. Each stimulus was tested for two sessions. The discrimination training resulted in distinct nonoverlapping response distributions. The generalization test data, presented as a gradient in the top part of Figure 3 where the median IRT (A to B time) is plotted against the test stimuli, show that the median IRT was a continuous function of the click rate: As intermediate stimuli were pre-



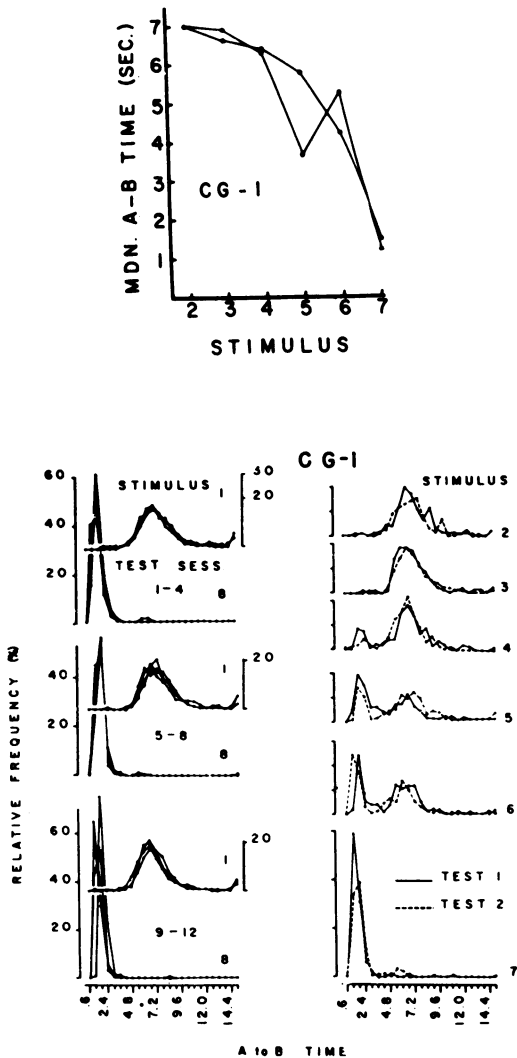


Fig. 3. (Top) The median A to B time (inter-response time) plotted against the test stimuli. (Bottom) The relative frequency distributions for performance during all 12 test sessions (two tests per test stimulus). The left column of curves shows performance on the original training stimuli for the 12 sessions with the distribution for Stimulus 1 displaced upward. The right column of figures shows the performances (including replications) in the presence of each of the six test stimuli (from Migler, 1964, p. 306).

sented, the IRT became intermediate to those IRTs established during previous training.

To examine the possibility that median IRT did not represent individual responses, Migler also presented the distributions of IRTs that occurred during the individual test stimuli. These data are presented in the lower part of

Figure 3. The left column shows the relative frequency of IRTs made during the presentation of training stimuli collected from the test sessions. The right column displays the relative frequency of IRTs during the presentation of the test stimuli. The IRT distributions (left column) collected during presentations of the training stimuli are distinct and nonoverlapping, thereby providing a concurrent and stable baseline by which to compare the data from the test stimuli. The IRT distributions collected during presentations of the test stimuli, shown in the right column, also are bimodal. The modal IRTs are identical to those obtained during presentations of the training stimuli. The relative frequencies of the two modal IRTs change as functions of the value of the testing stimulus. These data not only support the quantal interpretation of stimulus generalization, but also show that statistically summarizing the data may mask multiple controlling stimulus-response relations.

A similar two-key DRL procedure was used by Scheuerman, Wildemann, and Holland (1978). Using pigeons as subjects, they reinforced successive key pecks in the presence of a 1250-Hz tone if the interval between the key pecks was greater than 4.6 s and did not exceed 6 s. In the presence of another tone (2500 Hz), a pause of 1.0 to 2.33 s between successive responses was reinforced. Once responding was stabilized, the probability of reinforcement was decreased to .3, and then stability was achieved under the new reinforcement density. Using this reinforcement probability, tests of stimulus generalization were conducted in which stimuli (1479-, 1688-, and 2222-Hz tones) intermediate between the training stimuli were presented on unreinforced trials.

For 1 subject, the discrimination training resulted in an overlapping distribution of IRTs, rendering interpretation of the generalization-test data difficult. For the other 2 subjects, a substantial number of short IRTs occurred in the presence of the tone correlated with differential reinforcement of long IRTs (1250 Hz); that is, these subjects emitted short IRTs in one baseline condition that ideally should be unimodal around the reinforced

value of 4.6 s. This result is not surprising. DRL schedules typically, although not universally (Harzem, 1969; e.g., Migler, 1964), engender bimodal distributions of IRTs with one mode at or about the minimum reinforced IRT (e.g., 6 s) and another mode at short IRT values of less than and including 1 s (Kramer & Rilling, 1970). The variables responsible for this bimodality have not been specified (Harzem, 1969; Zeiler, 1979), but research investigating the role of multiple controlling stimulus-response relation should employ distinct baseline conditions. The IRTs obtained at a nontraining value during one of the training or baseline conditions by Scheuerman et al. weakens the conclusions that may be drawn.

Nonetheless, during the generalization test, the IRT distribution was bimodal and the relative proportions of responding at those modes changed as the stimuli were changed. This finding is similar to the findings of the other previously reviewed studies. In the Scheuerman et al. (1978) study, however, it is impossible to determine what proportion of short IRTs made during the presentation of test stimuli was due to the current stimulus conditions and what proportion was engendered by the DRL contingencies themselves.

One study (Boakes, 1969) obtained results demonstrating a continuous relation between IRTs and the dimension of the training stimuli. The procedures in this study were similar to those used by Migler (1964). Four pigeons were trained to peck two keys in succession. IRTs between 1.33 s and 1.66 s were reinforced in the presence of a luminance-intensity level of 301 cd/m<sup>2</sup> and IRTs between 5.33 and 6.66 s were reinforced in the presence of another luminance intensity of 246 cd/m<sup>2</sup>. Three other birds were trained in identical fashion except that the stimuli correlated with the reinforced IRTs were counterbalanced such that the brighter stimulus (301 cd/m<sup>2</sup>) was correlated with the contingencies for long IRTs and the dimmer stimulus (246 cd/m<sup>2</sup>) was correlated with the contingencies for short IRTs.

Results from the discrimination training indicated that the two behavior patterns were under control of the contingencies and the cor-

related stimuli. Also, there was little overlap in the two response distributions. Data from generalization tests (involving the training stimuli and seven intermediate stimuli) indicated that intermediate IRTs were obtained during the presentation of intermediate stimuli for 3 of 4 subjects in the group in which the brighter stimulus was paired with the contingencies for the short IRTs. The other subjects did not exhibit intermediate IRTs, but instead exhibited varying proportions of IRTs already trained. Additionally, Boakes mentioned that he used very similar procedures with 2 monkeys, and that intermediate IRTs in the presence of intermediate stimuli were not found, irrespective of whether the short IRTs had been reinforced in the presence of the high- or the low-intensity stimulus.

Boakes' (1969) study is significant in that it demonstrated a continuous relation between the length of the IRT and the value of the stimulus, but only if the higher intensity stimulus was paired with the shorter IRT. Although this study may limit the generality of the quantal interpretation, the suggestion that a continuous relation between stimulus and response dimensions will result from pairing short IRTs with a high-intensity stimulus is restricted by the other studies reviewed in this section. For example, Crowley (1979) did not obtain intermediate response durations to intermediate stimuli even though for some of his rats shorter response durations were paired with brighter stimuli. Similarly, Migler (1964) did not find a continuous relation with rats when short IRTs were correlated with a higher frequency cps stimulus. Scheuerman et al. (1978) provided some data; although somewhat inconclusive with respect to the quantal interpretation, they nonetheless indicated that a continuous relation was not obtained with pigeons when short IRTs were paired with high-frequency tones. Finally, Boakes (1969) did not obtain similar results when he replicated his procedures with rhesus monkeys.

Boakes' (1969) results may therefore result from processes specific to the relation between the intensity of visual stimuli and the pigeon's key peck. There is some support for this conclusion. First, the research on autoshaped be-

havior has shown that pigeons are phylogenetically predisposed to peck an illuminated key correlated with food presentation, despite the absence of a dependency between pecking and food presentation (Brown & Jenkins, 1968; cf. Schwartz & Gamzu, 1977). Also, there are data suggesting that the proportion of short latencies emitted by pigeons increases under certain conditions as luminance intensity increases (Blough & Blough, 1978). Further research addressing the limitations placed on the quantal interpretation by Boakes' finding is indicated.

#### *Response Dimensions Engendered by Schedules of Reinforcement*

If schedules of reinforcement are fundamental determinants of behavior (Morse & Kelleher, 1970), the distinction between the research reviewed in this and the preceding section is arbitrary. It is made here because the response dimensions examined in the two studies reviewed here are characteristic of research on schedules (cf. Ferster & Skinner, 1957). The first study investigated the contribution of multiple controlling stimulus-response relations in the analysis of stimulus generalization by using schedules to establish different response rates (Migler & Millenson, 1969). The second study used the characteristic patterns of responding engendered by different reinforcement schedules as the response dimension (Nelson & Farthing, 1973).

Migler and Millenson (1969) differentiated response rates by programming two different parameter values of the same reinforcement schedule. In the presence of a 2.5-cps stimulus, responses on a lever to the left of the food tray were reinforced on a VI 30-s schedule of reinforcement. In the presence of a 25-cps stimulus, responses on a lever to the right of the food tray were reinforced on a VI 226-s schedule. Subsequent generalization tests involved 1-min presentations of sounds with click-rates of 0.4, 1.6, 2.5, 9.5, 15.6, 20, 25, and 55 cps.

The discrimination training resulted in widely divergent response rates. Subjects 1 and 2 responded at rates of 1.2 and 0.8 responses per second, respectively, in the pres-

ence of the 2.5-cps stimulus and at rates of 0.4 and 0.2, respectively, in the presence of the 25-cps stimulus. The mean response rate (averaging across both the left and right levers) during generalization tests showed a steep gradient of intermediate response rates when the 9.5-, 15.6-, and 20-cps stimuli were present, but the running-rate measures calculated for the individual levers were similar to those obtained during discrimination training. Running rate, the number of responses emitted divided by the time in which responding was engaged (Catania, 1968), eliminates two components of responding from the calculation of rate—that is, the interval to the first response and periods of pausing. Migler and Millenson's running-rate data suggest that the intermediate response rates obtained with the mean-rate measures were due to averaging of periods of high response rates on one lever with periods of responding at a lower rate on the other lever. Similar effects have also been obtained in stimulus-compounding research (Bushnell & Weiss, 1978; Weiss, 1972).

The second study, by Nelson and Farthing (1973), investigated stimulus generalization in terms of the patterning of behavior, as measured by an index of curvature (Fry, Kelleher, & Cook, 1960; Gollub, 1964). The index of curvature reflects the extent and direction of the difference between an obtained cumulative response curve and the (hypothetical) straight line curve produced by a constant rate of responding. Nelson and Farthing used the index to characterize response patterns generated by multiple second-order schedules. The multiple schedule (FI 80 paired with a horizontal line; VI 80 s paired with a vertical line display) was combined in a second-order schedule (in which the performance engendered by one schedule requirement is treated as a response unit that is then reinforced under another schedule [Kelleher, 1966; Marr, 1979]). The second-order schedule used by Nelson and Farthing reinforced, on the average, every third (VR 3) completion of either the FI 80-s or the VI 80-s schedule. The completion of each 80-s segment resulted in a 20-s blackout. After 80 sessions of exposure to the multiple schedule, a test of stimulus generali-

zation was conducted under extinction conditions in which 0-, 30-, 60-, and 90-degree lines were randomly presented.

During discrimination training, index of curvature values of +0.04, +0.04, and 0.00 were obtained from the VI component. These low values are indicative of constant response rates, typical of VI schedule performance (Ferster & Skinner, 1957). The index of curvature values obtained from the FI component were +0.21, +0.19, and +0.12, suggesting a slight positive acceleration but a fairly constant overall rate. These values obtained from the FI component are small relative to those from other studies (e.g., 4.5 to 6.5) utilizing similar FI parameters (Gollub, 1964). The small values obtained by Nelson and Farthing may be due to the interaction between the FI and VI components. Fixed-interval schedules have been shown to be affected by the other schedules operative in a multiple schedule (Barrett & Stanley, 1980; Ferster & Skinner, 1957). Nonetheless, the FI pattern of responding was not sufficiently differentiated from the VI performance to allow unequivocal analysis of the generalization data.

The generalization test showed that there were continuous changes in the index of curvature such that the value of the index decreased as the test stimuli diverged from the FI-correlated stimulus and approached the VI-correlated stimulus. Although the results show a continuous relation, some qualifications should be noted. First, as just noted, the baselines were too similar to allow unequivocal conclusions. Second, the generalization test was conducted in extinction that may disrupt schedule performance and increase variability in responding (Rilling, 1977). Generalization tests conducted in extinction are less than optimal for the assessment of controlling relations; a steady-state procedure would have avoided this problem. The third qualification pertains to an implicit assumption of Nelson and Farthing that FI performance is a unitary response sequence; that is, the responses that constitute the features of FI performance are under control of the same variable or variables. There is, however, some disagreement about that assumption. For example, Schneider (1969)

characterizes FI performance as being composed of two states; the first state is the pause period occurring early in the interval, and the second state is the accelerated responding occurring later in the interval (cf. Gentry, Weiss, & Laties, 1983).

A study conducted by Wilkie (1974) supports Schneider's notion and deserves mention in its own right. Wilkie correlated a tilted line with an FI schedule of reinforcement. Once stability was obtained, a test of stimulus generalization was conducted by presenting a line varying in the degree of tilt during the test trials. Separate generalization gradients were shown for successive thirds of the test interval. The gradient from the first third of the interval resulted in a U-shaped gradient, typical of stimuli correlated with contingencies for not responding. The gradients plotted with data from the last third of the interval resulted in an inverted U-shaped gradient, typical of stimuli correlated with contingencies for responding. This result suggests that the same stimulus correlated with an FI schedule participates in more than one controlling relation. Thus, the behavior on an FI schedule under stimulus control may not be unitary. If two types of controlling relations were generated by the FI schedule used in Nelson and Farthing's study, then to interpret their generalization data appropriately, the two types of control would have to be specified and tracked during tests of stimulus generalization. The index of curvature measures responding throughout the interval and thus may have provided a measure that averaged across the controlling relations. Consequently, before Nelson and Farthing's data can be adequately evaluated, further research is necessary to identify the different controlling relations engendered by FI schedules.

#### *Responses Along a Dimension of Fundamental Frequency*

In order to investigate the contributions of two controlling stimulus-response relations in the analysis of stimulus generalization, Cross and Lane (1962) trained college students to emit two responses from a vocal continuum in the presence of auditory stimuli. Fundamental

frequency, the frequency at which vocal folds vibrate (Pickett, 1980; Yost & Nielson, 1977), was the defining property of the vocal response upon which reinforcement was dependent. In the presence of a narrow-band noise with a center frequency of 5,000 cycles per second (cps) presented at 56 dB, humming responses with a fundamental frequency of 147 cps were reinforced. In the presence of the same noise presented at 74 dB, humming responses with a fundamental frequency of 227 cps were reinforced. Once the discrimination was acquired, a stimulus-generalization test was conducted by presenting all intensity levels arranged in 3-dB steps from 50 to 80 dB. Responses during the test were nondifferentially reinforced.

The data from the generalization tests showed that in the presence of stimuli at and around the training values, responses emitted were consistent with the discrimination training. As stimuli intermediate between the training stimuli were presented, the frequency of responses trained with respect to one value decreased and the frequency of responses trained with respect to the other value increased. Changes in response topography were not obtained. Cross and Lane (1962) replicated these results using responses that were not from a continuum (i.e., phoneme clusters). Risley (1964) reported a similar finding employing responses (i.e., response levers) that did not have a continuous dimension.

### *Summary*

The research reviewed in this section examined the role of multiple controlling stimulus-response relations in the analysis of stimulus generalization. The majority of findings supported the quantal interpretation. In almost all of the studies, responding was not found to vary continuously with changes in stimulus value. Rather, intermediate stimuli controlled varying proportional frequencies of the previously trained responses. The same data when represented by means or medians, however, would show a decremental gradient indicative of a continuous relation. The above studies suggest that averaging responses from many performances of a single individual may mask different sources of stimulus control.

Further, these studies demonstrate that a single stimulus may enter into more than one controlling relationship. This fact supports the assumption from the viewpoint of the quantal interpretation that an experimenter-specified stimulus may be involved in more than one relation. Two studies were found not to be consistent with the quantal interpretation. One of those studies (Nelson & Farthing, 1973) was difficult to interpret because of the measurement system and the procedures employed. The other study (Boakes, 1969) clearly showed a continuous relation when a higher intensity light was paired with short IRTs but not in the opposite case. This latter finding may be due to the phylogenetically predisposed nature of pigeons' pecking with respect to visual stimuli.

### MICROANALYSIS II: THE IDENTIFICATION OF OTHER CONTROLLING STIMULUS-RESPONSE RELATIONS

The contribution to generalization gradients of multiple relations can also be discerned by establishing a single relation, instead of explicitly establishing multiple controlling relations. In this approach, tests of stimulus generalization include attempts to identify other controlling stimulus-response relations besides the one trained by the experimenter. The weakness of this tactic is that a variable of experimental interest may be established by indirect or accidental contingencies and is not directly manipulated. The compensating strength of the tactic is that when successful it will demonstrate the existence and role of multiple controlling stimulus-response relations in experimental arrangements identical to those typically used in the study of stimulus generalization (cf. Rilling, 1977). In this section several studies are reviewed that identify controlling stimulus-response relations that were not explicitly trained by the experimenter. In these studies either multiple behavior patterns were observed or response position was analyzed.

#### *The Observation of Multiple Behavior Patterns*

One way to identify multiple relations is to measure a large number of the responses emit-

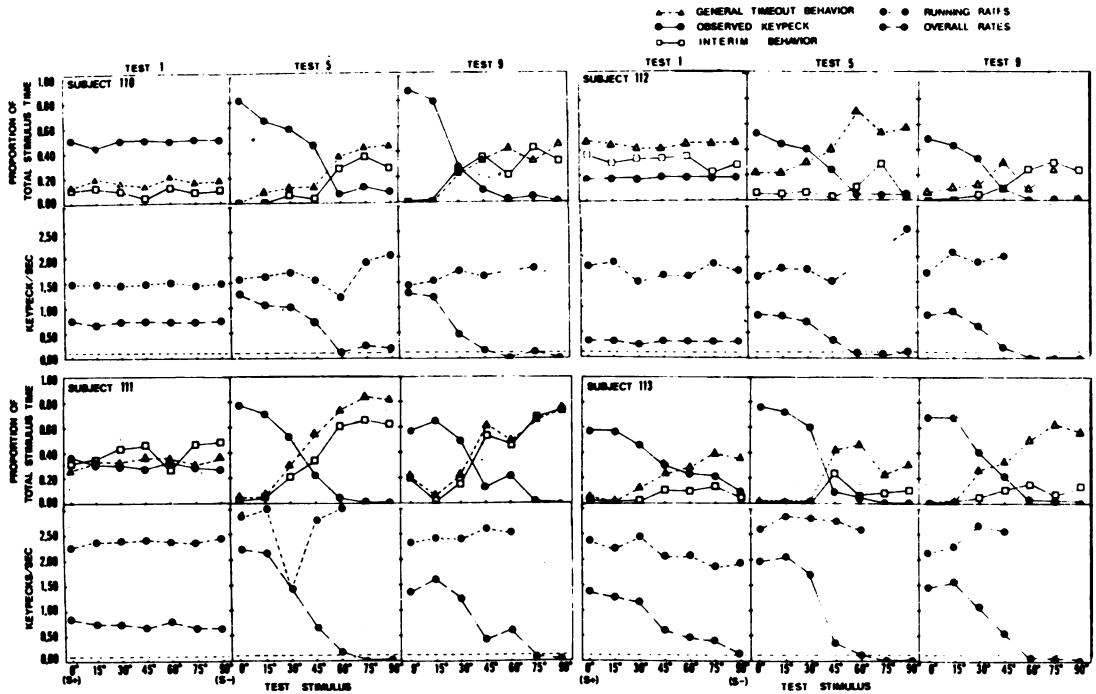


Fig. 4. Generalization gradients of three classes of behavior (timeout behavior is represented by filled triangles; interim behavior is represented by open squares; key pecking is represented by filled circles). Generalization gradients are shown separately for overall (single-break lines) and running (short-dashed lines) rates of key pecking. These data are from generalization tests 1, 5, and 9 (from Rand, 1977, p. 114).

ted during experimental sessions other than those directly related to the schedule dependency. This is precisely the approach adopted by Rand (1977), who established a multiple VI 60-s EXT schedule with pigeons. The VI schedule correlated with the presentation of a horizontal line and extinction was correlated with a vertical line. Subsequently, nine sessions of generalization testing were conducted, each separated by five sessions of discrimination training. In addition to key pecking, which was specified in the schedule dependency, Rand also measured the other responses similar to some previously selected by Staddon and Simmelhag (1971), including wing flapping, pacing, pecking, preening, and roosting. For each subject, Rand categorized these patterns into two types: interim behavior (behavior correlated with low probability of reinforcement) and timeout behavior (behavior that removes a stimulus correlated with extinction). Unfortunately, these classes were not mutually exclusive. For example, "turning

around in chamber" and "pacing along wall" were categorized as both interim and timeout behavior for Subject 111.

The discrimination training resulted in a high overall rate of key pecking in the presence of the horizontal line (S+) and low overall rates in the presence of the vertical line (S-). As discrimination training progressed, the overall rate of responding in the presence of S- decreased and concomitantly the time allocated to interim and timeout patterns increased. Data for 4 subjects from the first, fifth, and ninth sessions of generalization testing are presented in Figure 4. In the presence of S+, a large proportion of time was spent key pecking and very little time was allocated to the other measured behavior. In the presence of S-, key-pecking rates were minimal and a large proportion of time was allocated to the interim and timeout behavior. Stimuli intermediate between the training stimuli resulted in intermediate proportions of time allocated to key pecking, interim, and timeout behavior.

The generalization data obtained in Rand's study were taken from sessions in which extinction conditions were in effect. Consequently, this study is subject to the criticisms raised above concerning the use of extinction in the measurement of stimulus generalization. Nonetheless, the study shows that particular forms of behavior reliably occur in the presence of an S-. Further, this study obtained similar gradients for the behavior explicitly established by the experimenter and for the behavior not directly controlled by the schedule dependencies. Also, the same intermediate stimuli were found to occasion different responses at different times. From Rand's results we may infer that the decrement in overall response rate obtained during the presentation of intermediate stimuli may not result from changes in local response rate, but may instead result from the increase of other behavior patterns occurring, perhaps, between bouts of key pecking. (The results of the running response-rate measures from this study are discussed below in the section "Response rate reduction during tests of stimulus generalization.")

#### *Analysis of Response Position*

Analysis of response position has been used in two studies to identify inadvertently generated controlling stimulus-response relations. One study, reported in a chapter by Ray and Sidman (1970), used an eight-key simultaneous discrete-trial discrimination procedure. Ray and Sidman reinforced responses of 2 rhesus monkeys to a vertical line (S+) while responses made on the horizontal line (S-) were extinguished. After the discrimination was established, a generalization test was conducted by presenting stimuli intermediate between the training stimuli. With one subject (R15), a shallow intermediate generalization gradient was obtained; the gradient obtained with the other subject (R8) was sharp and peaked. Both subjects were also found to exhibit a position bias. Ray and Sidman reasoned that "control by key position could either compete with control by line tilt or interact with line tilt in such a way that the animal pressed the preferred position only when it

contained a vertical or near-vertical line" (p. 209). To determine which type of control was exhibited, gradients were plotted for responses on the preferred key and for responses on all other keys. Subject R8, which exhibited a steep and peaked overall gradient, exhibited a peaked gradient for both preferred and nonpreferred keys. For this subject, control exhibited by the preferred key and that of the line tilt were compatible. R15, which exhibited a flat overall gradient, exhibited a shallow intermediate gradient for the preferred key and a peaked gradient for the nonpreferred keys. The overall gradient for this subject resulted from averaging together two incompatible sources of stimulus control. Thus, this research indicates that an intermediate gradient could mask multiple controlling relations. In some instances responding was controlled by experimenter-specified stimuli and on other occasions by stimuli not even designated by the coordinates of the generalization gradient (Stoddard & Sidman, 1971b).

A similar arrangement was employed by Sidman (1969) to investigate the proposition of the quantal interpretation suggesting that changes in the shape or form of the gradient result from the development of controlling relations not specified by the experimenter. This assumption is counter to the descriptive stimulus-control assumption that the flattening of a peaked gradient results simply from decreases in the amount of differential control exerted by test stimuli. To address these assumptions, Sidman used monetary reinforcement in training 7 neurologically impaired human subjects to match to sample different-sized ellipses (ratio of minor to major axis). Delays of varying length (between 0 and 40 s) were then imposed between the presentation of the sample and the choice stimuli. Sidman plotted the deviations per opportunity from a perfect match as a function of delay. For example, if the sample was a circle (1.00 ratio of minor to major axis) and a subject pressed the panel showing a .89 ellipse, then this would be scored as a deviation from perfect matching of -.11. With simultaneous matching-to-sample procedures in effect, subjects exhibited steep peaked gradients with few deviations from perfect matching.

As the delay interval increased, the gradients became progressively flatter. Sidman also generated theoretical gradients based on the assumption that subjects' choices were independent of samples—that is, they were controlled entirely by the choice display. Thus, the theoretical gradients displayed a distribution of responses among choices in proportion to the relative frequency of each choice. As the gradient became increasingly flat, the theoretical and empirical gradients matched. Many of the subjects, however, exhibited a few more accurate choices than would be expected if their behavior were controlled solely by the choice display. Sidman concluded that both the control by the sample and the control by choices independent of samples contributed to the shape of the obtained gradients, but that "the relative contribution of each varied as a function of the delay interval" (Sidman, 1969, p. 750).

Sidman's results are not consistent with the descriptive stimulus-control assumption that the same stimuli control, but to a lesser extent, as a gradient flattens. Rather, Sidman demonstrated that intermediate and flat gradients result from multiple controlling relations—some specified by the experimenter and others inadvertently generated.

### *Summary*

Together, the experiments reviewed in this section show that reliable relations between stimuli and responses may be generated without the experimenter explicitly establishing them. These relations were also found to contribute to the shapes of intermediate and flat gradients. Sidman (1969) further showed that when a gradient became increasingly flat, stimuli that usually would be unspecified controlled large proportions of the measured response. These studies are important because they document the occurrence of multiple unspecified relations and that those multiple relations contribute to the shape of the obtained gradients. These studies, however, are few in number. Many more instances are required in many other experimental arrangements before the generality of these findings can be ascertained.

### MICROANALYSIS III: ANALYSIS OF RESPONSE RATE

During generalization testing the overall rate of responding is commonly observed to decrease as the stimuli diverge from the training stimulus or S+. The descriptive stimulus-control interpretation would suggest that these data demonstrate the existence of a continuous relation between response rate and the dimension of the training stimulus (Terrace, 1966). This position implicitly assumes that response rate is a unitary measure and that the decrement in rate is relatively homogeneous, involving proportionately longer IRTs.

The quantal interpretation disagrees with both of these assumptions. First, it does not assume that response rate is necessarily a unitary event. Just as different instances of a response dimension may be involved in more than one controlling relation, so might the individual responses that comprise overall rate. Second, even if response rate in a given instance were a unitary measure, the quantal interpretation questions the notion that the decrement in overall response rate during tests of stimulus generalization is homogeneous. The quantal interpretation instead suggests that if a stimulus presented during a generalization test is in the class of stimuli comprising the controlling stimulus-response relation, then the response rate to the test stimulus should be identical to the response rate made to the training stimulus. The reduction in response rate observed during tests of stimulus generalization must result from averaging the rate measure across two or more controlling stimulus-response relations. One such relation may involve responding to the test stimuli at the same rate as the rate obtained in the presence of the training stimulus. The other relation may involve periods of not responding (i.e., engaging in some other unmeasured behavior) controlled by the experimenter-specified stimulus or by some other concurrently available stimulus. To determine the validity of these assumptions, studies conducting microanalyses of response rate during stimulus generalization are reviewed.



*Response Rate and Multiple Controlling Relations*

Gray (1976) conducted a study examining whether response rate exhibited unitary properties. The key pecks of pigeons were reinforced according to a DRL 8-s schedule in the presence of a 570-nm light. After stable responding was obtained, a steady-state generalization procedure was administered in which 12 test stimuli, ranging from 560 nm to 582 nm in 2-nm steps, were presented. Interspersed with the test stimuli were presentations of the training stimulus with the DRL 8-s schedules in effect. Three of 5 birds exhibited a large proportion of reinforced IRTs on the DRL 8-s schedule accompanied by flat generalization gradients (gradients based on total responses). The other 2 birds exhibited a small proportion of reinforced IRTs on the DRL schedule and showed steep and peaked gradients. In addition to recording the total number of responses emitted during the presentation of the test stimuli, Gray also recorded the IRTs. Generalization gradients were plotted for each IRT class interval. The 3 birds that emitted a large proportion of reinforced IRTs had sharp and peaked gradients for all IRT class intervals meeting the minimum criterion required for the presentation of a reinforcer. Those class intervals that did not meet the criterion for reinforcement showed either a flat or a V-shaped function. The birds that emitted a small proportion of reinforced IRTs exhibited sharp and peaked gradients for all IRT class intervals.

Gray's results demonstrated that the responses that constitute response rate need not be a unitary class of behavior and that averaging responses regardless of IRT may obscure stimulus control. This is similar to the findings of Wilkie (1974) described above, which showed that a stimulus entered into different relations as a function of temporal location within FI schedules. Together, these findings suggest that responses that constitute response rate may be involved in more than one controlling stimulus-response relation and (at least with temporal schedules) that time or events correlated with time may play an im-

portant role in generating those different relations.

*Response-Rate Reduction During Tests of Stimulus Generalization*

An IRT analysis can also be employed to investigate the decrement in response rate typically observed during stimulus generalization. For example, Sewell and Kendall (1965) examined the IRT distributions obtained during tests of stimulus generalization by reinforcing a pigeon's key pecks in the presence of a particular click frequency on a VI 1-min schedule of reinforcement. Thereafter steady-state generalization procedures were conducted. The IRT distributions obtained during the presentation of the test stimuli showed that the short IRTs (less than 1.2 s) remained unchanged. The long IRTs (greater than 10 s) increased in frequency as the test stimuli became increasingly distant from S+. These results have been replicated with VI schedules correlated with visual stimuli (Schaub, 1967), VI schedules with auditory stimuli (Crites, Harris, Rosenquist, & Thomas, 1967), DRL schedules with visual stimuli (Blough, 1963), and a schedule that reinforced the least-frequent IRT with visual stimuli (Blough, 1969).

These findings suggest that the behavior that is occurring during generalization tests may be described as periods of responding (bursts) bounded by periods of not responding (interburst intervals [IBIs]), with the length of the IBI increasing as stimuli diverge from S+ (cf. Schoenfeld & Farmer, 1970).<sup>2</sup> Lengthening of the IBI would result in a greater number of long IRTs (the response that initiates a burst), with short IRTs (responses that comprise a burst) being unaffected. Only indirect support for this conclusion is provided by these

<sup>2</sup>It is not the purpose of this paper to draw parallels between the analysis of behavior and physics, for they are available elsewhere (Marr, 1981). It is interesting, however, to compare the statements of the quantal interpretation with respect to the rate reduction observed during tests of stimulus generalization and the comments of Max Planck on the quanta of light, photons: "The photons (the 'drops' of energy) do not grow smaller as the energy ray grows less; what happens is that their magnitude remains unchanged and they follow each other at greater intervals" (Planck, 1936, p. 59).

studies, because IRT distributions do not provide information regarding the sequential relations among responses (Catania, 1968).

An analysis of running rate would indicate whether characterization in terms of increases in the IBI best describes the rate decrements observed during stimulus-generalization tests. Running rate is the number of responses that occur over a period of time bounded by pauses. Consequently, a running-rate measure would eliminate IBIs. In a previously discussed study, Rand (1977) conducted an analysis of running response rate during tests of stimulus generalization. Although she found a decrement in overall response rate as the test stimuli became increasingly distant from S+, running rate was unchanged; that is, the running-rate measures were equivalent for both training and test stimuli. The data of 4 subjects from the first, fifth, and ninth test sessions exemplify this point (lower plots for each bird in Figure 4). The overall response rate (single-break lines) shows a typical decremental gradient: Response rate decreases as the stimuli diverged from the S+ value. The running rate (short-dashed lines) did not change during the presentation of intermediate stimuli. Rand's study provides, then, direct evidence for the notion that the decrement in response rate is a result of averaging longer IBIs with local response rates identical to the rate emitted on the training stimulus. Further, Rand's study suggests that the unit of behavior may not be the individual response but rather the burst. If this is the case, there may be a lack of information on what comprises the behavioral unit in stimulus generalization. Presumably, the response measure employed should reflect the unit under investigation. Many studies examining stimulus generalization have used overall response rate as the response measure with the implicit assumption that this measure reflects the behavioral unit. This assumption can be questioned, given the research reviewed here, for overall response rate averages across bursts and IBIs, each of which may be controlled by different stimuli. Identification of the controlling stimuli may be impeded until the unit of behavior is identified and tracked as stimuli are presented.

One study limits the generality of the above

conclusions. White (1973) examined the IRT distributions obtained during tests of stimulus generalization. He reinforced the key pecking of pigeons according to a VI 20-s schedule in the presence of a tilted line of 45°; a 15° line was correlated with extinction. When 80% of all responses occurred during the S+, a stimulus-generalization procedure was conducted using seven test stimuli ranging from 0° to 90° in 15° steps. This generalization test, conducted under extinction conditions, was administered for only one session.

The results showed that all IRT classes were affected in a similar fashion by test stimuli. As the values of the test stimuli became increasingly distant from S+, there was a decrease in the frequency of responses in all IRT classes. There are many variables that may account for these results including, perhaps, the extinction procedures. The most relevant variable may be the length of discrimination training, for the numbers of sessions between the introduction of the S- and the administration of the generalization test were three for one bird and four for the other. The training may have been insufficient to establish a behavioral unit.

A study by Schwartz (1981) supports this view. Schwartz reinforced any one of 70 possible sequences of eight pecks on two keys. One group of 5 pigeons received 20 sessions of sequence training and a second group of 5 received 50 sessions of sequence training. Each bird developed a stereotypical response pattern that occurred on about 90% of all trials. After sequence training, both groups were exposed to extinction conditions for up to five sessions. Extinction increased the latency to the initiation of a sequence for the group that had extensive training, but did not affect either the pattern of responses or the time to complete that pattern once initiated. The group that received less training exhibited longer latency to the initiation of a sequence, longer time to complete a sequence, and more variability in the response pattern under conditions of extinction. Schwartz's study shows that extinction conditions will more easily disrupt a behavioral unit if it is less extensively trained.

Perhaps the length of White's (1973) training procedure was not sufficient to establish a be-

havioral unit larger than individual pecks and consequently each key peck was susceptible to the effects of stimulus change as well as to extinction. Experimental verification, of course, would be needed to substantiate this possibility.

### Summary

In this section, studies have been reviewed suggesting that response rate is not unitary and that the responses that constitute rate can be under control of different stimuli. Also, the research cited indicates that the response-rate reductions described in stimulus-generalization research may be due to averaging periods of responding with other periods in which responding does not occur.<sup>3</sup> Consequently, overall response rate may not be the most productive behavioral measure for characterizing stimulus generalization. Rather, the burst and interburst interval may be better suited for characterizing stimulus generalization. Overall response rate was found to be a valuable measure in one study (White, 1973) in which individual IRTs as well as overall response rate were influenced by the presentation of test stimuli, but the small number of discrimination training sessions may account for those results. Overall, the findings suggest that there is no single adequate specification of the behavioral unit for the study of generalization. If the behavior unit could be specified, its occurrence and nonoccurrence could be analyzed and correlated with the momentary stimulus conditions, thereby providing a better description of stimulus generalization.

## IMPLICATIONS OF THE QUANTAL INTERPRETATION

The quantal interpretation has implications

<sup>3</sup>After this paper was typeset, a study by Mandell and Nevin (*Journal of the Experimental Analysis of Behavior*, 1977, 28, 47-57) was brought to our attention. Mandell and Nevin found the invariant response rates similar to the findings of the other studies reviewed in this section but found evidence that this invariance would occur only under conditions in which there was lack of an explicit choice response and relatively infrequent reinforcement. This finding may be very important in understanding constraints on the quantal viewpoint and deserves further study.

for the phenomenon of peak shift, for the appropriate level of analysis, and for the identification of behavioral units. Each will be considered in turn. In addition, similarities and differences between the quantal interpretation and stimulus-sampling theory will be discussed.

### Implications for Peak Shift

According to the quantal interpretation, generalization gradients often result from averaging together several controlling stimulus-response relations. The different relations can be easily and inadvertently averaged together because test stimuli appear to exhibit conditional control which in turn makes the specification of different controlling relations difficult. Peak shift, the displacement of maximum responding to one side of the training stimulus in the direction opposite the other training stimulus (Purtle, 1973), may be considered a special result of combining quantal units. Specifically, peak shift may result from averaging together the control exerted by two or more stimulus classes that overlap along some dimension to such an extent that the training stimuli themselves would exhibit conditional properties (cf. Blough, 1969). Hence, only stimuli to the side of the one training stimulus in the direction opposite the other training stimulus would provide a response measure that was not an average of those two stimulus-response relations. The stimulus that did not exhibit that conditional control would constitute the shifted peak (see Chase, 1983).

Given that peak shift is a derived phenomenon resulting from two separate controlling stimulus-response relations, then, the quantal interpretation would specify some additional conditions necessary for it to be obtained. Specifically, the two relations must be sufficiently different that when they are averaged, a change from the training response measures can be discerned. Thus, peak shift would be obtained when either one of the responses is unmeasured, as is typical of most generalization procedures (e.g., Hanson, 1959), or when both responses are individually measured such as in a two-response procedure (Blough, 1969). However, if the two responses are not separately measured, to obtain peak shift the re-

sponses must consist of widely divergent values (cf. Galloway, 1973; Yarczower, Dickson, & Gollub, 1966) so that the measure of central tendency for a given test stimulus will provide a response measure different from those obtained during training trials. Peak shift, then, should not be obtained if there is no overlap between the controlling stimulus-response relations, or when the two responses are very similar and not measured separately (e.g., Yarczower et al., 1966).

#### *Appropriate Level of Analysis*

Although the quantal interpretation tends to be supported by the research in this paper, the descriptive stimulus-control interpretation would be supported were the same data summarized and presented in a more molar fashion. Which level of analysis is most appropriate—the molecular analysis or the molar analysis—or are both levels of analysis appropriate descriptions of the data? Morris, Higgins, and Bickel (1982) argue that:

Just as the power of a microscope must be adjusted as a function of the phenomenon under study, so too does the level of behavior analysis need to be adjusted to the functional unit of behavior-environment interaction. To be specific, when order is not apparent at a molar level, a more molecular analysis may be necessary. . . . Conversely, if one fails to find an immediate stimulus that controls a response, perhaps the response is only an element of a larger functional unit which is controlled by currently operating variables not immediately attendant to that element. (pp. 119-120)

Unfortunately, there are no guidelines for the a priori selection of a particular analytical level. Fortunately, analysis at one level does not preclude analysis at another, so the appropriate approach can be determined empirically. For example, Catania (1962) examined the local and overall properties of behavior on concurrent schedules and found that overall mean response rate was orderly, lawful, and independent of variations in the local pattern. The local analysis of responding did not reveal any order. For those arrangements under ex-

amination, Catania concluded that the molar approach was more valuable. But with a different concurrent schedule arrangement, Shimp and Hawkes (1974) found a molecular approach more effective. They concurrently reinforced two classes of IRTs. While reinforcement frequency was held constant for the short IRT, the frequency of reinforcement for the long IRTs was increased. As reinforcement rate increased there was a concomitant decrease in overall response rate and an increase in the frequency of the long IRTs. Shimp and Hawkes concluded that the results were better interpreted in terms of IRTs than in terms of response rate inasmuch as the reinforced response (long IRTs) was increasing in frequency. Although concurrent schedules were used in both these studies, a different analytical level was found to be appropriate in each case.

Similarly, in a study reviewed earlier, White (1973) examined both response rate and IRTs and found that both changed continuously as the test stimuli were changed. Both analytical levels reflected the change and either analysis would be adequate. Migler (1964), on the other hand, found that the molar analysis obscured features of the local performance and artifactually suggested a continuous relation between stimulus and response dimensions where none existed. In that instance, the molecular level best reflected the effects of the stimulus manipulations. Until an a priori method of selection of the appropriate analytical level is devised, the most prudent approach is to conduct analyses at both (or a variety of) molar and molecular levels and examine which level best displays order without obscuring important characteristics of the subject's performance (Sidman, 1960; Zeiler, 1977). This is particularly apt in the study of stimulus generalization because continuous relations between stimulus and response dimensions could either reflect the moment-to-moment behavior of the subject or be artifacts of measures of central tendency. By examining both analytical levels these two sources of continuity can be discerned.

#### *Identification of the Behavioral Unit*

Arguments regarding the appropriate level

of analysis have been ongoing for some time now and will probably continue to generate discussion (e.g., Moore, 1983). Conceivably, the appropriate level of analysis is secondary to and follows from the unit of behavior selected for study (Shimp, 1979; Staddon, 1967). On this issue the quantal interpretation has important implications.

It is generally agreed that a unit of behavior is identified when a functional relation is shown between classes of stimuli and responses (Branch, 1977; Catania, 1973; Skinner, 1935, 1938). When a change is made in some aspect of the environment—for example, changing an FR schedule to extinction—a functional relation is assumed if a correlated change in the response occurs. With respect to stimulus control, a controlling stimulus-response relation is identified by using the tactic of stimulus variation (Honig, 1970; Ray, 1969; Riley, 1968; Terrace, 1966). A property of the stimulus is changed and a functional relation is assumed if there is a correlated change in the response.

Given the research reviewed in this paper, it is doubtful whether the tactic of stimulus variation is sufficient to ascertain a controlling stimulus-response relation. Stimulus variation may produce correlated changes in several controlling stimulus-response relations. If a measure is taken that averages across several of those relations, orderly data may still be obtained, but the identification and description of the individual controlling stimulus-response relations may be obscured (Sidman, 1969, p. 756).

Some researchers and theorists have proposed, in addition to the functional relation criterion for the identification of a behavioral unit, that a criterion of invariance also be adopted (Marr, 1981; Shimp, 1979; Staddon, 1967). In this context, invariance refers to the unchanging relation between the defining properties of the stimulus and response (cf. Stevens, 1951). For example, Skinner (1953, p. 116) has detailed how a stimulus, a spot in the visual field, and a response, touching that spot, may vary widely in topography but remain invariant with respect to the relationship between the spot seen and touched. The invariance criterion assumes, then, that the controlling relationship is unchanging. This is not

to say that a functional relation cannot change, but rather that the invariance criterion pertains only to functional relations during steady-state periods.

The notion of invariance coupled with identification of functional relations is, in essence, the tactic used in the quantal interpretation of a controlling stimulus-response relation. A controlling stimulus-response relation is an integral unit. When a stimulus is presented that is a member of the stimulus class that comprises the controlling stimulus-response relation, the full-blown response occurs. When a stimulus is presented that is not a member of the stimulus class that comprises the controlling stimulus-response relation, the response does not occur. When a stimulus is presented that sometimes occasions the behavior and at other times does not, then further stimulus variation is required to determine the invariance of the stimulus. For example, a stimulus that sometimes occasions a particular type of behavior and at other times does not may be composed of elements, some of which are only occasionally presented (Touchette, 1969), or the control exerted by that stimulus may be conditional on some other stimulus such as the previous training trial. Each of the possibilities could then be manipulated.

With respect to experimental tactics for the identification of a controlling stimulus-response relation, the notion of invariance of a functional relation translates into Sidman's (1980) homogeneous data subsets. Homogeneous data subsets entail identifying correlations of 1.0 between an available stimulus and the responses emitted. For instance, suppose an accuracy score of 0.5 is obtained in a discrete-trial two-choice discrimination procedure in which the positions of S+ and S- are randomized. From these results, the inference could be made that behavior is random, or that each stimulus controlled behavior on half of the available trials. Another alternative would be to employ the tactic of homogeneous data subsets—examine the total environment and determine what stimuli are correlated in a near-perfect fashion with the obtained behavior. In the above example, an examination of responses with respect to the right or left position

may yield a positive correlation between responses and the right position and a negative correlation between responses and the left position. Thus, examining homogeneous data subsets will permit the identification of stimuli not specified by the experimenter, but which nonetheless set the occasion for behavior. The obtained correlation, however, does not necessarily define the controlling stimulus-response relation. Further, stimulus variation would be necessary to determine the specific defining property of the correlated stimulus.

The notion of invariance and its embodiment in the tactic of obtaining homogeneous data subsets were exemplified by several of the studies reviewed here that revealed invariant relations with respect to the properties of the response. As previously noted, however, all the studies failed to identify the invariance on the stimulus side of the controlling stimulus-response relation; that is, they did not specify the variables responsible for the conditionality of class membership of intermediate stimuli. These conditional stimuli need to be identified to ascertain the invariant stimulus conditions. Nonetheless, a useful experimental approach may be to determine controlling stimulus-response relations by varying properties of the stimuli and noting unity between stimulus presentations and the measured response. If a homogeneous relation between stimuli and responses is not obtained, then "the appropriate experimental strategy is to analyze the actual stimulus-control topographies [the controlling stimulus-response relations], not to theorize about excitatory or inhibitory control by stimuli that may actually not control at all" (Stoddard & Sidman, 1971b, p. 153).

#### *Relation to Stimulus-Sampling Theory*

The quantal interpretation bears some similarity to stimulus-sampling theory (Estes, 1950, 1959). Both theories propose that stimuli control in an all-or-none fashion (cf. Guthrie, 1935, 1959), and that each stimulus may be composed of many elements. Stimulus-sampling theory contends that only a subset of these elements will be sampled and will control responding at any one instance. The factors determining which set of elements will be sam-

pled are multitudinous and are for all intents and purposes uncontrollable. Thus, stimulus-sampling theory proposes that the factors determining whether a stimulus will control a response in a given instance are probabilistic; it follows that under stimulus-sampling theory, attempts at experimental control are supplanted by attempts at improving the estimates of the probability function. On the other hand, under the quantal interpretation, the factors determining whether a given stimulus will control behavior are considered to be identifiable and controllable via experimental manipulation. The invariance criterion provides the means by which those factors may be discerned. If the momentary determinants of stimulus control prove to be unspecifiable, subscribing to probabilistic processes may be necessary and would provide a more striking relation with quantum physics. But, as in quantum physics, subscribing to probabilistic processes should result from the failure to find the controlling variables, and should not be selected a priori.

#### CONCLUSION

Much of the research here suggests that the quantal interpretation provides a viable formulation of stimulus-generalization data. With few exceptions, the data do not support the notion of continuous relations between stimulus and response dimensions in stimulus-generalization gradients. Rather, the controlling stimulus-response relations may be quantal, functioning as integral units. The typical continuous gradients of stimulus generalization have been found in many instances to mask several discrete controlling stimulus-response relations. The argument could be made, however, that discrete responses are defined for the subject and the fact that those discrete responses are emitted is not at all surprising. Further argument could be made that to observe continuous gradients, measurements need only be made of some other response dimension not specifically trained (e.g., latency). Of course, there is always a possibility that another behavioral dimension other than those measured in the above studies did change in a contin-

uous fashion; if that were the case, the finding would be of great interest. However, the responses considered in the research reviewed here were not chosen arbitrarily. Since the inception of generalization research, the property of behavior that has been measured has been the defining property of the operant (e.g., Guttman & Kalish, 1956)—that is, the response feature that has been either differentially conditioned, reinforced, shaped, or trained (Skinner, 1935, 1938). In the above studies the property measured was the property of behavior upon which the training contingency was specified; in most instances those measures were shown to be quantal. If some other feature of the behavior is shown to have a continuous function, that finding should be further investigated; it may be that the application of the quantal interpretation is limited to the defining property of the operant.

Although the quantal interpretation seems to characterize much of the research reviewed here, several studies did support the descriptive stimulus-control interpretation and indicate that phylogenetic constraints and limited discrimination training may result in a continuous relation between stimulus and response dimensions. More research investigating the propositions of the quantal interpretation, other response dimensions, and these limiting cases is necessary before the generality of the quantal interpretation can be known. Hence, exclusive validity of one or the other of these two formulations cannot be asserted at present. If the quantal interpretation leads researchers to effective action (Zuriff, 1980) and if it can account more convincingly for the data than other formulations can, then it will be accepted. Conversely, rejection of the descriptive stimulus-control interpretation would occur only if that interpretation failed to be an effective research tool and if another more convincing account became available.

At least one of the conditions for the acceptance of the quantal interpretation appears to be operative. In a recent review Honig and Urcuioli (1981) suggested that active research on stimulus generalization has been declining in recent years, in part because of the limitations of using response rate as a measure of

stimulus generalization. Because the quantal interpretation provides guidelines and tactics for evaluating response rate, the stage may be set for a very interesting and perhaps controversial period in the analysis of stimulus generalization.

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