ON THE DISCRIMINATIVE CONTROL OF CONCURRENT RESPONSES: THE RELATIONS AMONG RESPONSE FREQUENCY, LATENCY, AND TOPOGRAPHY IN AUDITORY GENERALIZATION[1]

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Human subjects were used in a study of auditory generalization following multiple-response discrimination training. The relations observed among stimulus intensity, response probability, and response latency were invariant with respect to whether the two vocal responses conditioned were topographically discrete, as in one experiment, or topographically continuous, as in another. The major findings were:

1. The probabilities associated with a specific response were maximal over several stimulus values at the extreme ends of the continuum, then dropped sharply at stimuli intermediate to the initial S^D's as the probability of the alternative response increased.

2. Overall response latency was inversely related to the relative frequency of the two responses at each stimulus value. When the two responses were most nearly equal in probability, latencies were maximal; when one response had close to unit or zero probability, latencies were minimal.

3. Analysis of the latencies of the two responses, taken separately, revealed: (a) an increase in latency as the difference between the test stimulus and the initial S^D increased; (b) a sharp discontinuity in the latency gradient and reversal in trend at intermediate stimulus intensities; and (c) at a given stimulus value, latencies associated with the stochastically dominant response were consistently shorter than those of the nondominant response.

4. No changes in response topography (fundamental frequency) were correlated with the characteristic changes in probability and latency during stimulus generalization.

Previous studies of stimulus generalization have analyzed the invariances in behavior that occur despite changes in the controlling stimulus *following single-response training.* However, discriminative behavior is often acquired by the concurrent conditioning of several responses, each under the control of a different discriminative stimulus. The simplest experimental paradigm appropriate to this investigation is discrimination training with two mutually incompatible responses, each reinforced in the presence of a different S^D. Reinforcement and extinction are reciprocal operations here because the S^D for one response is also an S^Δ for the other. Two questions arise: (1) What are the properties of stimulus generalization following this conditioning procedure; and (2) how does this behavior compare with that following single-response conditioning?

The present study answers these questions by examining the changes in probability, latency, and topography of human vocal re-sponses caused by changes in an auditory discriminative stimulus.

EXPERIMENT I

In this experiment, the vocal responses were the phonemic clusters /ka/ and /ti/. These responses may be termed topographically discrete because the articulatory gestures necessary to produce them involve different parts of the vocal apparatus, and the ranges of topographical variation associated with the two responses do not overlap. Topographically discrete responses were selected so that response generalization would be minimal, and thus the findings in stimulus generalization would not be confounded. The effect of both types of generalization operating together will be examined in Experiment II.

Method

The subjects were 14 male and 6 female volunteer undergraduates, who served individually in 40-min sessions. The subject was seated in an anechoic chamber in front of a counter, signal light, and microphone. Auditory stimuli were presented monaurally

through a binaural headset with calibrated earphones (PDR-8). The stimuli were 1.2-sec, 500-cps tones recorded on magnetic tape at 3-db intervals over a 30-db range. To eliminate print-through signals and reduce noise during playback of the recording, an electronic switch (Grason-Stadler Model No. 829S119) and a narrow bandpass filter (Dytronics) were interposed between the tape recorder output (Ampex 300-4) and the headphone.

Pulses synchronized with stimulus onset were recorded on a second tape track; these closed the electronic switch, so that the stimulus reached the headphone, and also triggered an electronic counter (Hewlett-Packard 522B). The subject's response to the stimulus operated a voice relay (Miratel) which, in turn, stopped the counter. The start-stop interval was read in milliseconds from the counter and taken as the latency. If S failed to respond, the time intervals were automatically terminated after 5.5 sec by stop pulses recorded on a third track of the tape. All control apparatus was located outside of the experimental chamber.

Procedure

After the subject was seated in the anechoic chamber, these instructions were read:

"You can earn money by simply saying /ka/ or /ti/ at appropriate times. We can't tell you now when or how these responses should be used. That is for you to learn. All you have to do is wear this headphone and watch the display unit in front of you. You will hear various sounds. Each time you respond appropriately the green light will flash and five points will be added to your score on the counter. You will want to get as high a score as possible because the amount we pay you at the completion of the experiment will be determined by your final score."
(Questions were answered only by a repeat of the instructions.)

Training. The subject was given 140 500-cps tones in random order, half at 56 db and half at 74 db (SPL). The 56-db tone was the discriminative stimulus (S^D_1) for a /ti/ response (R_1), and the 74-db tone was the discriminative stimulus (S^D_2) for a /ka/ response (R_2). The S^D_1 was the S^Δ for R_2, and the S^D_2 was the S^Δ for R_1. If a single /ti/ response followed S^D_1 or a single /ka/ response followed S^D_2, within

the allowed time interval (5.5 sec), reinforcement was provided on each of the first 10 occasions. After that, a partial reinforcement schedule was used, with probability of reinforcement equal to .30. However, the schedule was adjusted to insure that both responses would be reinforced an equal number of times. At the end of the training phase, the experimenter re-entered the chamber.

Testing. The subject was told that the experiment would continue as before, but with one change. Although the points earned for appropriate responses would "continue to accumulate on the counter in the other room," his own display unit would be inoperative. The counter and signal light were disconnected and the display moved out of view.

The subject was given 110 stimuli in random order at 11 intensity levels arranged in 3-db steps from 50 to 80 db SPL. Thus, 5 intensity levels intermediate to the two S^D's were sampled, as well as 4 intensities outside the range initially established.

Results

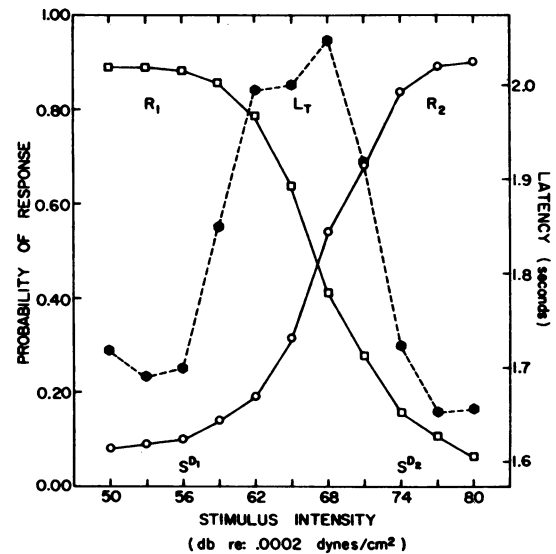Figure 1 summarizes response probability and latency data for all 20 subjects. Each

Fig. 1. Conditional probabilities of R_1 and R_2 and the average of their combined latencies at each stimulus intensity. The conditional probabilities were estimated from the total number of /ka/ responses (squares) and /ti/ responses (circles) emitted in 10 presentations of each stimulus intensity to each of 20 Ss. The total latency (hexagons), L_T, at each stimulus intensity is the unweighted mean of the average latency of responding by each of 20 Ss.

circle is an estimate of the conditional probability, when stimulus i is presented, of the R_1 response previously conditioned to S^D_1; similarly, the squares give P (R_2/S_i). These estimates are based on the relative frequency of both responses in a sample comprising 200 presentations of each S_i. The R_1 and R_2 probability functions are not exact complements of one another, since S was not instructed to respond to each stimulus. The total number of responses the 20 Ss emitted to each stimulus varied from 190 to 199; the lowest totals occurred at the middle stimulus values. Most of the individual gradients manifested the same general trends depicted in Fig. 1. In most instances, response probabilities did not peak at the S^D intensities; instead, they were maximum over an extended range of stimulus intensities at the extremes of the continuum. Intersubject variability in the estimated response probabilities was observed to be a nonmonotonic function of stimulus intensity.

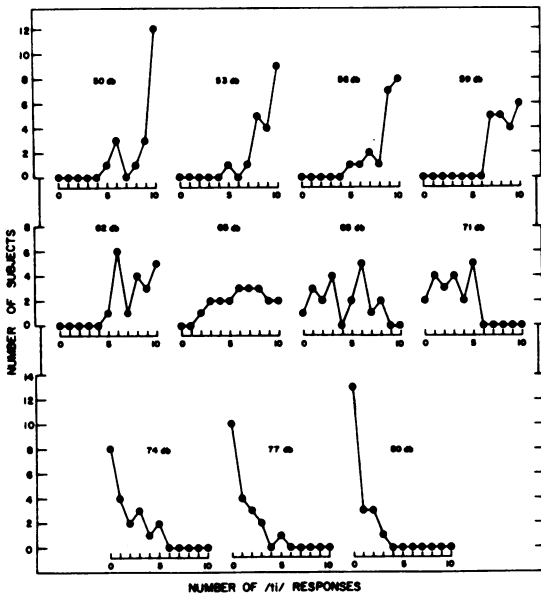For each stimulus intensity, Fig. 2 shows the number of Ss who emitted the response

Fig. 2. The number of subjects who emitted the discriminative response /ti/ an indicated number of times at each stimulus intensity. (For example, on six of the presentations of the 62-db stimulus, six subjects responded /ti/.)

/ti/ the indicated number of times. Variability is smallest at the extreme intensities and increases systematically to a maximum at the median stimulus intensity.

The dotted curve in Fig. 1 shows the average latencies for the two responses combined. Examination of response latencies reveals minima when the probability of one response was high and the other low. Any change in response probabilities toward equality was correlated with increased latencies; the latency function reaches a maximum when the probabilities of the two responses are most nearly equal. Figure 3 presents a breakdown of the total latencies
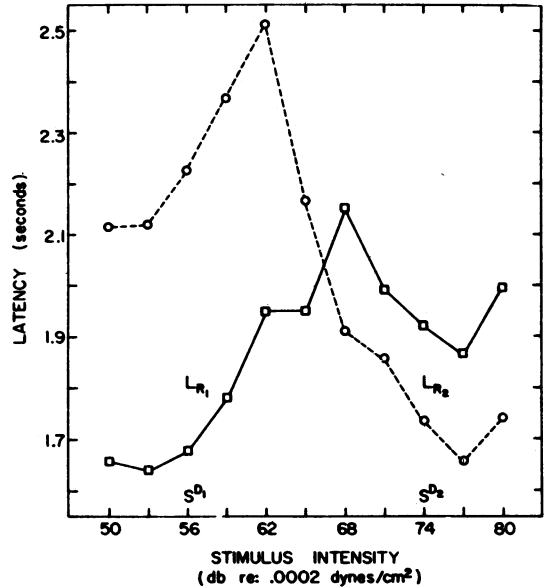

Fig. 3. Comparison of the two response-latency gradients relative to stimulus intensity. Each point represents the average latency of R_1 (squares) and R_2 (circles) responses emitted by 20 Ss.

into those associated with R_1 and R_2. Latencies accompanying the stochastically dominant response (the response with the highest probability of occurrence at a given stimulus intensity) are consistently shorter than the latencies associated with the nondominant response. This relation also holds for the data of individual Ss, although some Ss emitted too few nondominant responses to yield a reliable estimate of the corresponding latencies. When individual data are pooled, both latency functions increase to a maximum at a point displaced 12 db from their respective S^D intensities, and then they decrease systematically. (See Discussion.)

Since all subjects were given the same amount of discrimination training during the first phase of the experiment and an arbitrary learning criterion was not imposed, the gen-

eralization data could be partitioned with respect to how well the initial discriminations were formed. The subjects were divided into two groups of 10, each on the basis of the number of incorrect responses emitted during the second half of the training session, that is, the last 70 stimulus presentations. The number of "errors" (S^D_1: R_2 and S^D_2: R_1) of the subjects in Group I varied from 1 to 7, with an average of 3.6. The number of errors of subjects in Group II varied from 10 to 29, with an average of 15.7. The R_1 and R_2 generalization gradients for the two groups were similar to those in Fig. 1. The major differences between the two groups were the greater degree of generalization and the greater number of responses emitted by Group II. (Group I emitted 1051 responses out of a possible 1100, and Group 11 emitted 1091.) Comparison of the latency functions revealed a third difference. Group I had appreciably higher maximum and lower minimum latencies than Group II. The inverse relation between the ratio of response probabilities and the latency at each stimulus intensity holds for each of the two groups as well as for their combined data. Figure 4 shows the results for some individual Ss who are representative of the groups discussed. The relative frequency of
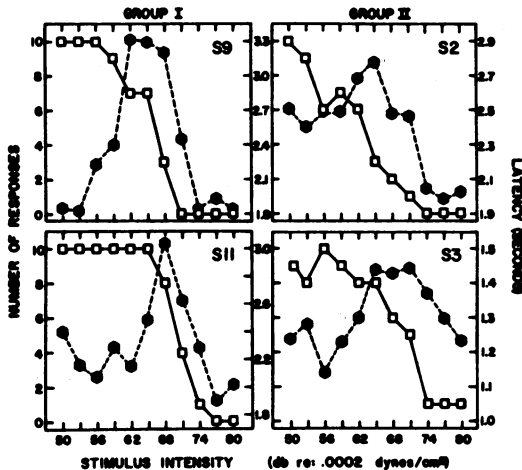

Fig. 4. Generalization gradients of representative individual Ss in Experiment I. The squares represent the number of R_1 responses, and the hexagons represent average latency of total responding for each stimulus intensity. Subjects S2 and S3, selected from Group II, committed 13 and 14 errors, respectively, during the last half of discrimination training. Subjects S9 and S11, selected from Group I, each committed 3 errors during the last half of discrimination training.

only the R_1 responding is presented for these Ss. Obviously, the general relations among stimulus intensity, response probability, and latency observed for the group are also true for individual Ss.

EXPERIMENT II

In the preceding experiment, two vocal responses were used that were mutually incompatible and topographically discrete. In the present experiment the basic conditions of Experiment I were replicated. However, in order to examine the possible effects of stimulus-response interaction, two vocal responses were used that were topographically continuous. These responses differed only with respect to fundamental frequency, the acoustic correlate of a topographical continuum (tension on the vocal cords) along which response generalization may be observed and conveniently measured.

Method

The subjects were 14 male students, none of whom had participated in the preceding experiment. The apparatus and procedure were basically the same as in Experiment I, with the following exceptions. A pitch meter and graphic level recorder (General Radio Type 1521-A) were used to measure and control the fundamental frequency of an S's responses. The former device consisted primarily of a series of filters and electronic switches, arranged so that the fundamental frequency of the vocal response could be selected from the complex speech signal, and a frequency meter (Hewlett-Packard Model 500 BR) which transformed this sinusoidal input into a DC output voltage proportional to the input frequency. The DC output of the meter was applied to the graphic level recorder for an instantaneous, real-time display of the pitch level of the emitted response.

Procedure

The procedure differed from that of the preceding experiment in that a lengthy session for shaping the desired responses was necessary before discrimination training could begin. The subject was seated in an anechoic chamber and given the following instructions:

"This is an experiment in pitch production. We want you to learn to produce two

levels of vocal pitch by humming. You will learn these pitches by producing a steady and continuous hum and maintaining it until one of the lights in front of you flashes on. If the middle, green light flashes, that will indicate that you have produced a correct pitch. You should stop and repeat it. If the top, red light flashes, your pitch is too high. You should stop and produce another pitch at a lower level. If the bottom, yellow light flashes, your pitch is too low. You should stop and try a higher pitch. We will start with one pitch level and work with it until you can produce it repeatedly without error; then we will switch to the other pitch. When you have learned to produce that one correctly, we will alternate systematically from one to the other to give practice on both. How well you learn to produce these pitches will help you later in the experiment to win money."

The two vocal pitches required of each *S* were 147 cps and 227 cps. A pitch production within ± 2 cps of that desired was reinforced.

If the subject could not reliably produce the pitches desired after 1 hr of shaping, he was excused from the experiment. If the pitches were produced to a criterion of 10 successful alternations, shaping procedures were terminated and discrimination training begun. From this point on, procedure followed that of the preceding experiment. Instructions to the subject were the same except that pitch level was substituted for /ka/ or /ti/ response. The lights signaling that the produced pitches were too high or too low were not used. Only the green light and addition of five points to *S*'s acore signaled a correct response.

The discriminative stimuli for the vocal responses were recorded at the same sound-pressure levels as those in Experiment I. Instead of 500-cps tones, however, the stimuli were 1.2 sec narrow band noise, with center frequency 5000 cps. Noise was used rather than tone because the 500-cps tones tended to produce changes in vocal pitch toward matching at 125 cps or 250 cps. Testing for generalization was carried out along the same intensity range as before, but with noise instead of tone stimuli.

Results

Of the twelve subjects who started in the experiment, seven satisfied the shaping crite-

rion and continued into the discrimination training phase. Of these seven, four subjects failed to emit one or the other of the differentiated pitches in the presence of the discriminative stimuli and were excused from the experiment. For the remaining three *S*s, the responses emitted during testing were analyzed with respect to variations in pitch. These were distributed between two response categories, called low (R_1) and high (R_2) pitch productions. The pitch continuum can be categorized in this way because these categories delimit two regions separated by an extended range within which no pitches were produced. Figure 5 presents the results separately for three of the *S*s. The median frequency (circles) and the range (vertical lines) of high- and low-pitch responses are represented as a function of stimulus intensity. The dotted horizontal lines (labelled f_1 and f_2) in each graph represent the absolute pitch levels differentiated in the preceding training session. Although two of the *S*s did not maintain these absolute levels accurately, the ratio of R_1 to R_2 pitch remains the same as that during training.

Figure 5 also shows the probability of an R_1 response at each stimulus intensity for each of the three subjects. There were no response omissions in this experiment; therefore, the R_2 function is the exact complement of the R_1 function for each *S* and is not shown. The functions labelled L_T represent the average latency of the responses emitted at each stimulus intensity. In general, the results agree with those of Experiment I. The latencies vary systematically with the probability of response functions, tending toward a maximum where response probabilities are nearly equal and a minimum where response probability is unit or zero.

EXPERIMENT III

In the preceding experiments, discrimination training procedures were used in which discriminative responses were reinforced under controlled conditions. In the present experiment, no attempt was made to condition discriminative behavior before generalization testing. The two vocal responses /do/ and /to/ were used. We presume that these responses were in the vocal repertoire of the subject, and that during prior verbal learning, the acoustic patterns correlated with these responses had
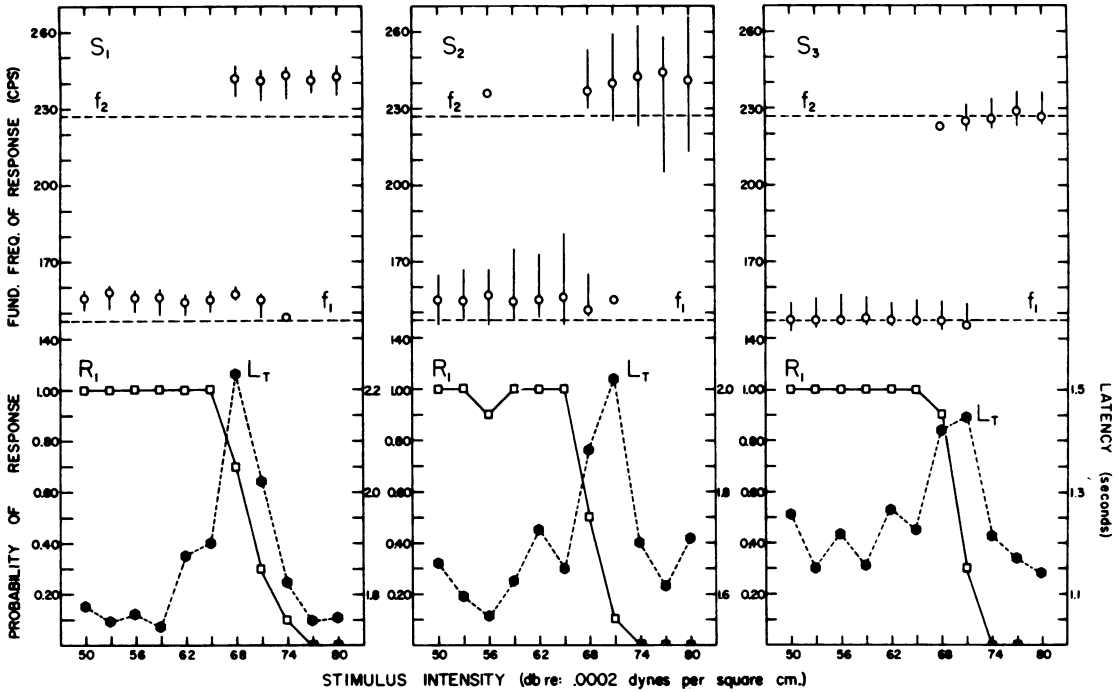
Fig. 5. Relations among response probability, latency, and topography in stimulus generalization.

Top: Median frequency in cps (circles) and the range (vertical lines) of high- and low-pitch responses as a function of stimulus intensity for each of three *Ss*. The dashed horizontal lines represent the vocal pitches previously differentiated.

Bottom: Response probabilities (squares) equal the ratio of the number of low-pitch responses emitted to the number of stimulus presentations (10) at each intensity. The hexagons represent the average latency of high- and low-pitch responses to each stimulus intensity.

acquired some discriminative control over the responses themselves. One property that distinguishes the acoustic patterns correlated with /do/ and /to/ is the relative onset time of their first and second formants. This variable defined a stimulus continuum which was sampled at seven points by means of speech synthesis techniques.

Method

In condition (a) of the experiment, *S* was instructed to respond with /do/ upon hearing the /do/ stimulus and /to/ upon hearing the /to/ stimulus. To demonstrate a possible interaction between previously conditioned discriminative responses and competing responses introduced in the experimental situation, a second condition (b) was studied in which the subjects were instructed to reverse their discriminative responses. In other words, instead of responding with /do/ to a /do/ stimulus, they were to respond with /to/; and, accordingly, they were to respond with /do/ to a

/to/ stimulus. In addition, a third condition (c) was studied in which /ka/ and /ti/ were substituted for the /do/ and /to/ responses. Presumably, this latter procedure would have the effect of introducing multiple competing response tendencies at stimulus values intermediate to the two basic speech sounds.

To obtain generalization gradients of frequency and latency for these responses, seven synthesized speech sounds were prepared using the Pattern Playback[2] to convert hand-painted spectrograms into sound. The spectrographic patterns used (shown in Fig. 6) were identical except for the relative onset time of their first and second formants: The first formant was "cut back" in 10-msec steps from 0 to 60 msec. Liberman *et al.* (1961) have shown that with normal adults, the relative frequency of /do/ responses decreases as the first formant cutback is increased.

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[2]For a description of the Pattern Playback and its use, see Cooper, F. S., Spectrum Analysis. *J. acoust. Soc. Amer.*, 1950, **22**, 761-762.
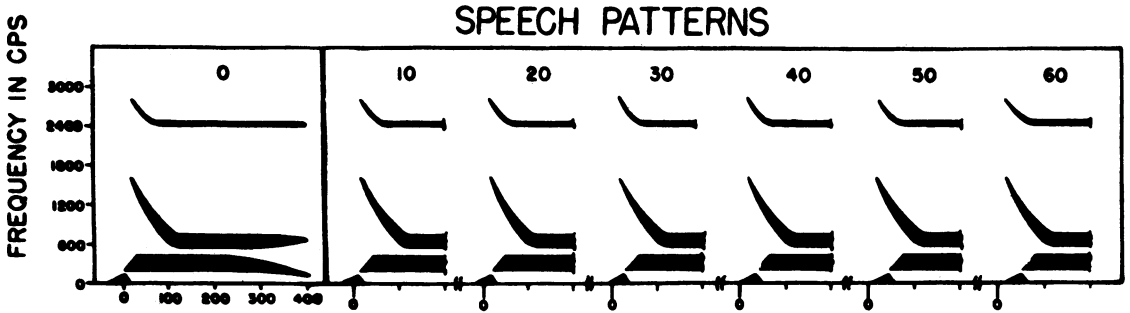
SPEECH PATTERNS

Fig. 6. Spectrographic patterns which were converted to sound by the Pattern Playback to form the speech stimuli of the experiment (after Liberman *et al.*, 1961).

Procedure. The apparatus and procedure were similar to those of Experiment I. The subjects were six undergraduate students who had not participated in the previous experiments. They were run individually for 90-min sessions. The subject was seated in an anechoic chamber and read the following instructions:

"When you put on the earphones, you will hear a series of sounds which resemble either /do/ or /to/. When you hear

/do/, call it (R_1). When you hear /to/, call it (R_2). Always respond to each sound."

In condition (a) the responses requested as R_1 and R_2 were /do/ and /to/, respectively. In condition (b), they were /to/ and /do/; and in condition (c), they were /ka/ and /ti/. Each subject served under all conditions, which were presented in counterbalanced order so that all permutations of the three conditions occurred.
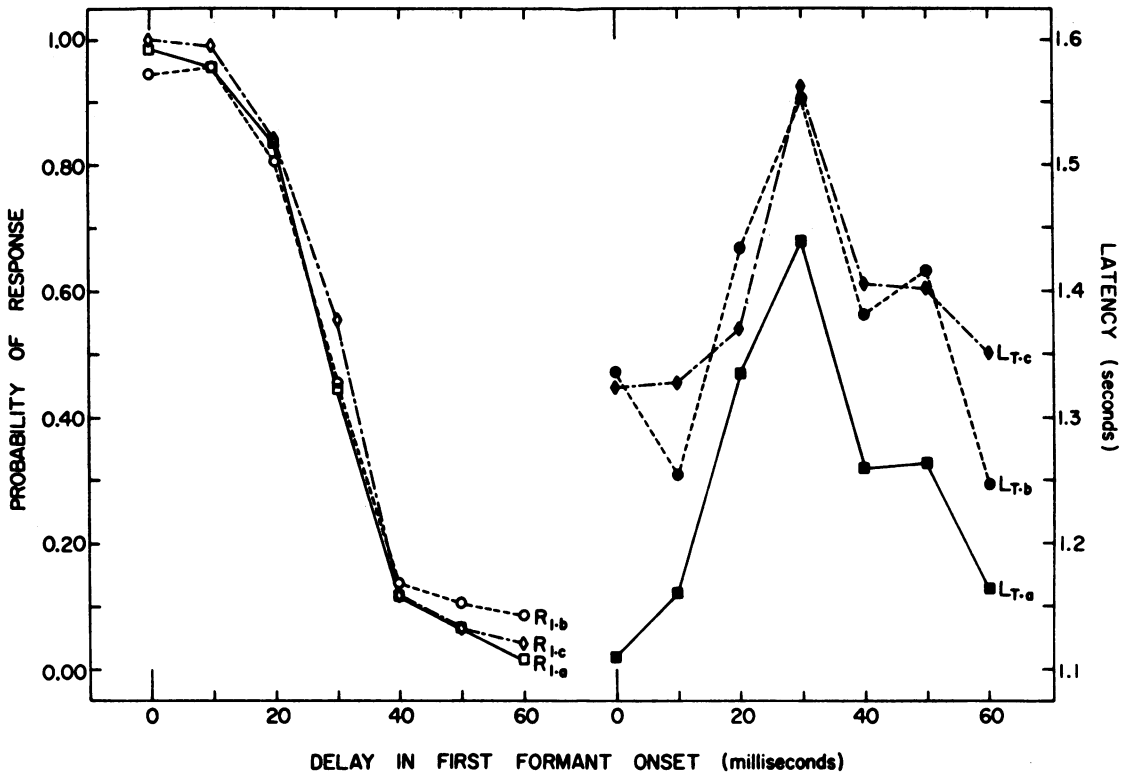

Fig. 7. Conditional probability and average latency of vocal responses to synthetic speech stimuli under three sets of instructions. (See text.)

Results

The results were highly consistent across individual subjects, and no systematic effect was observed related to the order in which the three conditions were imposed. Therefore, the data were pooled and the results analyzed on the basis of group totals. Overall, the results replicate the findings of the preceding experiments. As Fig. 7 shows, the gradients of response probability (representing the relative frequency of R_1 at each stimulus value) were not substantially different for the three conditions. Here, as in Experiment II, the R_2 gradients were exact complements of their respective R_1 gradients. The major "between conditions" effect was revealed in the analysis of response latencies. Figure 7 shows the average response latency at each stimulus value for the three conditions used. It is apparent that the overall latencies in conditions (b) and (c) were substantially longer than those in condition (a); however, the general shapes of the latency functions were similar. As Fig. 8
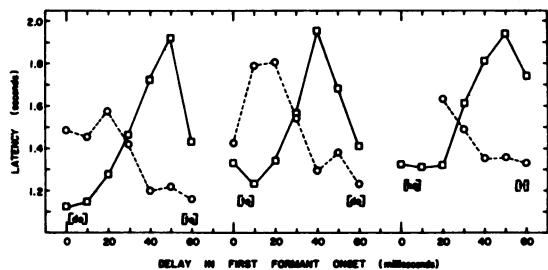

Fig. 8. The average latencies of the vocal responses (Fig. 7) partitioned in terms of their R_1 and R_2 components.

shows, separate analysis of the R_1 and R_2 latencies revealed the same effect observed in Experiment I, *i.e.*, the tendency for response latency to increase systematically and then decrease as the test stimulus was changed.

Discussion

The two major findings in these studies suggest that the detailed properties of stimulus control in multiple-response situations differ from those in the single-response case. First, the probabilities associated with a specific response were maximal over a large range of stimulus intensities, and then they decreased rapidly as the alternative response became dominant. This contrasts with the generalization gradients usually obtained following

single-response discrimination training, which have been described as depicting the "exquisitely precise tuning of the animal to [a particular] aspect of its environment" (Guttman, 1956). Most investigators have found discontinuous generalization gradients that peak at the training stimulus and decay at an exponential rate on both sides. Consequently, the exponential decay function has become the favored expression for describing the process whereby other stimuli acquire discriminative control over the response (Hull, 1952; Shepard, 1957). A generalization suggested by the *present* results is that multiple-response discrimination training effectively divides the stimulus continuum into more or less sharply defined, response-specific categories or classes (*c.f.* Fig. 1, 5, and 7). Stimuli within a given class are mutually substitutable with respect to their effectiveness in evoking the response appropriate to that class. The results of a recent study by Sherman and Pierrel (1961) support this formulation. Immediately following simple discrimination training, auditory generalization gradients were obtained from bar-pressing rats that were characterized by broad regions of equal response probability as a function of stimulus intensity. The observed gradients of response rate revealed a sharp peak at S^D only after continued discrimination training in which several S^{Δ} values were introduced, as well as the initial S^D and S^{Δ}. The gradients obtained in the early sessions were similar to those reported here. This formulation receives additional support from another quarter. In a review of research in the area of speech perception, Liberman (1957) reported that subjects identified speech sounds from a single acoustic dimension in such a way as to divide the stimulus continuum into discrete phoneme categories (*cf*. Fig. 7 of the present study). It should be noted that stimulus control may be "categorical" with respect to nominally scaled response events (*e. g.*, occurrence versus nonoccurrence of a response in a given unit of time) and still yield orderly variations in other measures of responding, such as rate, amplitude, or latency. In Experiment II, for example, response latency increased while response probability was unity or zero over several stimulus values.

The gradients of response latency observed in the present study was a second departure

from prior findings. Le Ny (1957) and Schlosberg and Solomon (1943) have reported that the time interval between stimulus onset and response is a monotonically *increasing* function of the difference between the test stimulus and the training stimulus. Moreover, response latency has generally been presumed to be inversely related to response probability. These generalities apply to only a restricted portion of the stimulus continuum in a two-response situation. In both Experiments I and II, the response-latency functions exhibited an unexpected discontinuity, and a change in the sign of their slope, at a stimulus value just beyond the middle stimulus. (See Fig. 3 and 8.) This "distortion" of the latency function must reflect the influence of a factor other than the generalization of the effects of reinforcement in S^D. The effects of this factor may be described if two assumptions are made: (1) The effects of reinforcement generalize in a similar manner for both responses; and (2) by averaging latencies for all responses emitted at a given stimulus value, these effects balance out and the resultant form of the latency function represents the effects of this additional factor. The factor is then found to be maximally effective at the stimulus values at which response probabilities were most nearly equal. (See Fig. 1 and 7.)

Two major findings emerge from an analysis of the relations between response probability and latency: (1) The mean latency for all responses at a given stimulus value varied as an approximately linear function of the variance associated with the obtained distribution of response probabilities; and (2) the latency of the stochastically dominant response was consistently shorter than that associated with the nondominant response. A psychophysical study reported by Kellogg (1931) corroborates both of these findings. Kellogg used seven fixed pairs of visual intensities as stimuli. In three of these pairs, the left half of the visual field had the lower luminance; in another three pairs, the right half had the lower luminance; and in the remaining pair, the fields were equal. In one condition of the experiment, S responded with either "left side darker" (R_1) or "right side darker" (R_2) to each stimulus pair, and latencies were recorded. Gradients of response probability and latency derived from these data are comparable with these of the present study (*cf.* Fig. 1 and 3).

Figure 5 shows that there is no systematic change in response topography correlated with the changes in response probability and latency discussed earlier. This finding is contrary to an expectation presented by Levine (1960). Levine proposed that if two discriminative stimuli from a single continuum control two mutually exclusive responses that "have some continuum qualities in common," *i.e.*, "can be differentiated on the basis of some stimulus attributes inherent in the way in which the responses are made available," then responses intermediate to the two conditioned responses will occur when stimuli intermediate to the two S^D's are presented. The conditions of Experiment (II) satisfy those stated by Levine: Two mutually exclusive responses, which could be differentiated and ordered along a continuum (*i.e.*, pitch), were conditioned to two discriminative stimuli; however, Fig. 5 shows that responses of intermediate topography were not observed when stimuli of intermediate intensity were presented. It should be noted that this finding is based on the results of a small sample of Ss selected on the basis of rather stringent experimental criteria.

The generalization gradients obtained when stimulus generalization sampled responses from the prior verbal repertory of the subject did not differ noticeably from those obtained following discrimination training in the experimental situation. However, Fig. 7 shows that when speech stimuli are used, the choice of the response pair affects the observed latency distribution. Under instructions to respond with /do/ and /to/ to stimuli that are typically called /do/ and /to/, respectively, the Ss gave shorter response latencies than when they were instructed to call these stimuli /to/ and /do/ or /ka/ and /ti/. One way of interpreting this difference in the latency distributions is to say that approximately 20 years of intermittent discrimination training with speech stimuli have yielded a reduction in response latency of approximately 100 msec.

The results obtained in Experiments I and II may presumably be generalized to other Class I, or prothetic, sensory continua, on which discrimination is characteristically mediated by an additive process at the physiological level (Stevens, 1957). We may inquire whether these findings may be further generalized to metathetic continua, in which dis-

crimination is mediated by a substitutive process. It is not known whether formant onset time, the variable defining the /do/-/to/ continuum of Experiment III, is a prothetic or metathetic variable. However, a study by LaBerge (1961), which in several respects parallels our own, used stimuli on a metathetic continuum (position of a small light along a vertical axis) and obtained results comparable to our own.

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