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Identification and discrimination of rise time: Is it categorical or noncategorical?

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Abstract

Previous studies have reported that rise time of sawtooth waveforms may be discriminated in either a categorical-like manner under some experimental conditions or according to Weber's law under other conditions. In the present experiments, rise time discrimination was examined with two experimental procedures: the traditional labeling and ABX tasks used in speech perception studies and an adaptive tracking procedure used in psychophysical studies. Rise time varied from 0 to 80 ms in 10-ms intervals for sawtooth signals of 1-s duration. Discrimination functions for subjects who simply discriminated the signals on any basis whatsoever as well as functions for subjects who practiced labeling the endpoint stimuli as "pluck" and "bow" before ABX discrimination were not categorical in the ABX task. In the adaptive tracking procedure, the Weber fraction obtained from the jnds of rise time was found to be a constant above 20-ms rise time. The results from the two discrimination paradigms were then compared by predicting a jnd for rise time from the ABX discrimination data by reference to the underlying psychometric function. Using this method of analysis, discrimination results from previous studies were shown to be quite similar to the discrimination results observed in this study. Taken together the results demonstrate clearly that rise time discrimination of sawtooth signals follows predictions derived from Weber's law.

INTRODUCTION

Within the last few years there has been a renewed interest in the identification and discrimination of nonspeech sounds. The theoretical motivation for studying perception of nonspeech signals has changed somewhat from earlier studies which simply attempted to demonstrate that "speech is special" (Liberman *et al.*, 1957, 1967; Mattingly *et al.*, 1971). Instead, a number of current investigations has been more concerned with finding natural sensitivities in the auditory system for nonspeech signals which might also serve as the underlying basis for acoustic features in the perception of speech sounds (Miller *et al.*, 1976; Pisoni, 1977; Schouten, 1980; Stevens, 1981).

In a widely cited study, Cutting and Rosner (1974) reported the first compelling evidence for categorical-like perception of nonspeech stimuli. They employed the typical procedures used in speech perception experiments—labeling in combination with ABX discrimination for variations in rise time duration at stimulus onset. The discrimination functions were nonmonotonic and showed a typical categorical peak in the middle of the rise time continuum. The generality of the perception results they obtained was extended to infants (Jusczyk *et al.*, 1977) and adults in cross-continua adaptation studies (Remez *et al.*, 1980).

Recently, however, Rosen and Howell (1981) have failed to replicate Cutting and Rosner's results using digitally generated stimuli. This failure led Rosen and Howell to measure the original Cutting and Rosner stimuli. They discovered that the differences in rise time were not equally spaced as had been assumed by Cutting and Rosner. In a series of experiments, Rosen and Howell then determined that categorical discrimination functions could be obtained with stimuli containing rise time intervals similar to Cutting and Rosner's, but not with stimuli spaced with equal intervals. In fact, for equal-interval stimuli subject's responses appeared to follow Weber's law. That is, the just detectable rise time difference increased with increasing rise time durations. The interpretation of the discrimination data in terms of Weber's law was in good agreement with an earlier psychophysical study conducted by van Heuven and van den Broeke (1979).

Cutting (1982) has recently published a response to the criticisms raised by Rosen and Howell (1981). In two experiments he replicated Rosen and Howell's result that equal-interval rise time stimuli are not categorically perceived. However, Cutting claimed that a constant Weber fraction model was not fully supported by the data either. Instead, Cutting pursued the investigation of rise time based on the following unusual prediction. He claimed that "if a Weber-fraction view is correct, stimuli generated with equal logarithmic increments of rise time ought to yield a flat discrimination function." Contrary to his predictions, Cutting's analysis of his ABX discrimination results showed that logarithmically spaced stimuli were generally perceived categorically. Thus Cutting concluded that there is a "general fickleness of the phenomenon of categorical perception in any stimulus domain" and that rise time can be perceived categorically. While these results may have surprised Cutting, categorical discrimination of nonspeech stimuli spaced logarithmically along a stimulus continuum has been reported previously in the literature. Burns and Ward (1978) showed categorical perception for musical intervals and Pastore *et al.* (1977) for auditory intensity. Difficulties in reconciling Cutting's results provided part of the motivation for the experiments described below.

In the present paper, we report three experiments designed to improve our understanding of the discrimination of rise time in nonspeech signals. Given the apparent controversy surrounding Rosen and Howell's (1981) results, the first experiment was a replication of the labeling and ABX tasks for a newly generated set of sawtooth stimuli. The second study employed a more sensitive psychophysical task to directly estimate the jnds for rise time for the same sawtooth stimuli. Finally, the third experiment compared the discrimination results obtained in the ABX and the psychophysical task using the same subjects. Our results showed that discrimination of rise time follows Weber's law, and that our analysis can account for the results from Cutting's (1982) logarithmic rise time continuum.

I. EXPERIMENT 1: IDENTIFICATION AND ABX DISCRIMINATION

A. Method

1. Stimuli—The stimuli generated for this experiment were intended to replicate as closely as possible the stimuli generated by Rosen and Howell (1981, experiment 3). A set of nine sawtooth stimuli was generated digitally on a PDP-11/34 computer. Each signal was synthesized by adding together in phase the first 11 sinusoidal components of a sawtooth waveform using a modified version of the program *SOUND* (Lovell and Carterette, 1972). The fundamental frequency was 300 Hz and the amplitude of the harmonics decreased in 6-dB steps from the 66.23 dB (11 bit) maximum at the fundamental. The amplitude envelope impressed at the onset of each stimulus rose linearly from 0 to its maximum in 1, 10, 20, 30, 40, 50, 60, 70, and 80 ms. The 1-ms ramp interacted with the fundamental of the stimulus so that this stimulus reached its maximum amplitude in about 3 ms. This stimulus will be nominally referred to as the 0-ms rise time stimulus in keeping with previous studies. From

the maximum, a second linear decay ramp was impressed over the remaining waveform which reached 0 in 1.02 s. Thus the overall length of the stimuli covaried with the duration of the onset ramps from 1020–1100 ms as in the previous studies reported by Rosen and Howell (1981) and Cutting and Rosner (1974).

The stimuli were output under computer control at a 10-kHz sampling rate through a 12-bit D/A converter. Stimuli were low passed once at 4.8 kHz, and then filtered through two cascaded low-pass filters (Krohn-Hite model 3202R) at 3500 Hz with a total roll-off of 48 dB per octave. The stimuli were then amplified to 82 dB SPL and routed to six TDH-39 headphones located in a quiet testing room.

2. Procedure—Two procedures were used to test the effects of labeling experience on discrimination performance. In the first procedure, subjects were initially trained to label the endpoint stimuli as “pluck” or “bow,” and were given the identification task before the ABX task. In the second procedure, only the ABX task was given.

a. Identification preceding ABX discrimination: All experimental tasks were controlled by a PDP-11/34 laboratory computer. Responses were collected on two-button response boxes equipped with feedback and cue lights.

The experiment consisted of two 1-h sessions conducted on successive days. The procedure was divided into three general parts: familiarization, identification testing, and discrimination testing. Four tasks were run on day 1. The first task introduced subjects to the 0- and 80-ms rise time stimuli, and their respective labels of “pluck” and “bow.” The second task involved training subjects to identify these two “endpoint” stimuli as “pluck” and “bow” using feedback. Next, this procedure was repeated with a different random order but *without* feedback. The results from this task were used to assess whether subjects met a predetermined criterion of 90% correct over the 40 trials to be included in subsequent parts of the experiment.

Following initial training, the identification task was run. Subjects were presented with the full set of 0- to 80-ms rise time stimuli randomized in two blocks of 90 trials each. Subjects were asked to identify each stimulus as either “pluck” or “bow.”

On day 2 the subjects who passed the criterion initially received a warmup sequence containing ten replications of the 0- and 80-ms stimuli for labeling with feedback. Subjects were then given one block of stimuli from the identification task again. The final task was a standard ABX discrimination test using feedback for the correct response. The response buttons were relabeled as “first sound” and “second sound.” All seven two-step pairs from the rise time continuum were presented 20 times each in all possible ABX triads for a total of 140 trials. Stimuli within the triad were separated by 1 s each.

b. ABX discrimination only: The same ABX discrimination test previously described was employed here. However, *no* training or identification tasks preceded the ABX task. Subjects in this condition were presented with two blocks of 140 trials each, a total of two times the number of ABX trials that the previous subjects received.

3. Subjects—A total of 38 subjects were recruited from a paid laboratory subject pool for both procedures. Subjects were native speakers of English with no reported history of hearing or speech disorders. They were paid \$3.00 per hour for each testing day.

In order to have an equal number of subjects in each procedure to facilitate statistical analysis, we determined in advance of testing that results would be analyzed from 15

subjects in each condition. Thus subjects with the poorest performance in the ABX task from each group were eliminated until 15 subjects remained. In the identification preceding ABX procedure, 21 subjects participated in the first day of testing. Three of these subjects could not identify the pluck and bow stimuli at the 90% criterion level and were excused from testing after day 1. Of the 18 subjects who completed both days, the three worst subjects on the ABX task with an average of 55% correct performance (chance = 50%) were dropped in the final analyses. In the ABX only procedure, data were collected from 17 additional subjects. The two poorest subjects with an average performance of 50% correct were not included in the final analysis.

B. Results: Identification preceding ABX: Results from the second day of testing averaged over all 15 subjects are displayed in Fig. 1. Identification results obtained on day 1 were considered as practice with the labeling task and were not analyzed further. Percent identification of each stimulus using the “pluck” response is plotted in Fig. 1 as a function of rise time duration. The overall shape of the identification function indicates that subjects classified the stimuli into two reasonably discrete categories of plucks and bows. Since this experiment was a replication of Rosen and Howell’s experiment 3, we may compare the present results to their findings (see their Fig. 3). From inspection, the two identification functions appear to be quite similar and have approximately the same crossover point between the pluck-bow categories at about 30-ms rise time.

The individual identification data for each of the 15 subjects showed sharp labeling functions using 100% pluck and bow responses for the endpoint stimuli (see Kewley-Port and Pisoni, 1981, for individual results). These consistent identification functions are no doubt the result of the criterion testing and practice given to subjects on day 1. Given these labeling functions, if listeners perceive rise time categorically, we would certainly expect to find categorical ABX functions from these subjects.

The ABX function averaged over all 15 subjects is shown in Fig. 1. This function shows an overall decrease in discrimination from 73%–53% correct as rise time increases in duration. The predicted discrimination performance from individual identification functions using the Haskins formula (Pisoni, 1971) is also plotted in Fig. 1 for comparison. As expected, the predicted discrimination function is quite categorical. However, the predicted and obtained functions do not match very closely and a within subject analysis of variance showed they were significantly different [$F(1,14) = 48.98, p < 0.001$]. Thus from these results we conclude that differences in rise time are *not* categorically perceived.

The group ABX discrimination function compares favorably with the results reported by Rosen and Howell (1981) in experiment 3 of their study. Both discrimination functions fell from around 75% correct discrimination for the 0- to 20-ms pair to near chance as rise time increased. Cutting (1982) has also replicated the major results of this study for a rise time continuum with linear increments of rise time. His stimuli differed considerably, however, in parameters such as period, size of the rise time increments, and range of rise times presented. More recently, Hary and Massaro (1982) have also published similar results for different stimuli in an identification and AX discrimination experiment. The overall results of these independent studies indicate that subjects can reliably classify rise time stimuli into discrete perceptual categories such as pluck and bow. However, subjects do not discriminate these stimuli in the ABX task in a categorical-like manner.

Rosen and Howell suggested that their ABX discrimination results could be predicted from Weber’s law with the signal detection analysis developed by Macmillan *et al.* (1977). Since we directly compared the ABX results with Weber fractions in experiments 2 and 3 below, we suggest the following as a simple test of Weber’s law for ABX functions. If the linear

correlation of ABX performance with rise time is high and negative, Weber's law holds. The linear correlation of the group data on Fig. 1 was -0.95 . The linear correlation of Rosen and Howell's ABX function calculated from data given in their Table 1 was -0.96 . In contrast, the linear correlation of an idealized categorical ABX function is zero. Therefore the discrimination results obtained in this experiment, as well as Rosen and Howell's, suggest that discrimination of rise time follows predictions derived from Weber's law.

C. Results: ABX only: In order to find out whether ABX discrimination of rise time stimuli would be different for subjects not previously introduced to the pluck and bow labels, data were also collected from subjects who participated in only the ABX discrimination procedure. Group results for 15 subjects in the ABX only procedure are displayed in Fig. 2. The left-hand panel of Fig. 2 shows the results obtained separately for block 1 and block 2 of this experiment. Discrimination improved significantly from block 1 (64.2%) to block 2 (67.9%) by a within subjects analysis of variance [$F(1,14) = 6.81$; $p < 0.03$].

Block 2 of the ABX only data is compared to the ABX data following identification in the first procedure (hereafter called ABX after ID) in the right panel of Fig. 2. Block 2 of the ABX only data is most comparable to the ABX after ID data because both groups had similar amounts of prior listening experience with the rise time stimuli. These discrimination functions are very similar overall and did not differ from one another in an analysis of variance. This similarity was obtained even though individual ABX functions for both procedures showed considerable variability. We conclude, therefore, that subjects' ability to label these rise time stimuli as plucks or bows apparently has little, if any, influence on their ability to subsequently discriminate differences along the continuum.

A detailed examination of the shape of both ABX functions in the right-hand panel of Fig. 2 revealed a slight peak in discrimination for the 10- and 30-ms stimulus pair. Since only slightly more than half of the 30 subjects actually showed an increase from the first to the second stimulus pair, the peak may be nothing more than a sampling problem. Whatever the reason, the overall shape of the discrimination functions is clearly *not* categorical. The ABX only function had a linear correlation of -0.94 with rise time durations, a value quite close to the -0.95 value for the ABX after ID function. Thus the results from both ABX conditions clearly suggest that Weber's law holds for discrimination of rise time in sawtooth signals. The motivation behind the next experiment was to test this hypothesis more directly using an appropriate psychophysical procedure for estimating jnds of rise time.

II. EXPERIMENT 2: DISCRIMINATION USING AN ADAPTIVE PROCEDURE

A widely used adaptive tracking procedure was chosen for this study. The transformed up-down procedure developed by Levitt (1971) for estimating the jnd of rise time was modified to run on-line from a minicomputer. Pilot studies with this procedure indicated that subjects initially found the discrimination task very difficult. Since our goal was to compare the jnds of rise time to the results obtained in the ABX task, the experiment was designed with the following task variables in mind. The ABX discrimination paradigm may be considered a very high-uncertainty discrimination task (Harris, 1952). Sachs and Grant (1976) have shown that task uncertainty influences the shape of the observed discrimination function. In particular, they obtained categorical-like discrimination functions for stimuli in a high-uncertainty task but not in a low-uncertainty task. Thus we decided to arrange our task as much as possible towards higher uncertainty conditions so that any tendency towards categorical perception of rise time might be revealed in the shape of the jnd function.

Method

1. Stimuli—Forty-five additional sawtooth stimuli were digitally generated. Each sawtooth waveform was generated from 11 harmonics as in the previous experiment. The duration of all waveforms, however, was fixed at 1 s. Stimulus amplitude rose linearly from 10.0–156.7 ms in 3.3-ms increments (i.e., the period of the 300-Hz fundamental) and then decayed linearly to 0 over the remainder of the waveform. The eight stimuli from 10–80 ms in 10-ms increments were the *base stimuli* used to estimate the jnds in discrimination. Rise time stimuli shorter than 10 ms were not used in this experiment because of the “thumpy” quality of these stimuli compared to longer rise time stimuli (see also Rosen and Howell, 1981, p. 163).

All stimuli were output and low-pass filtered in the same way as in the previous experiment. Subjects listened to stimuli over one pair of matched, calibrated TDH-39 earphones at 82 dB SPL in a sound-treated room (IAC model 401-A). Rise time duration at the earphones was carefully measured for each of the base stimuli using an artificial ear. The shape of the amplitude envelope at stimulus onset was clearly linear. The rise time values of the base stimuli were measured independently by two people and found to be the same as the nominal values, i.e., 10–80 ms.

2. Subjects—Four students working in the laboratory were recruited as paid subjects for the experiment. Subjects were unfamiliar with rise time stimuli and psychoacoustic experiments. All subjects were audiometrically tested for the octave frequencies from 500–8000 Hz using a Grason-Stadler model 1701 audiometer. Audiograms for both ears were within normal ranges of individuals in their age group of 19–23 years.

3. Procedure—Using a two-interval forced-choice task with feedback, the subjects were asked to indicate which item of each pair of stimuli had the “more gradual onset.” For each run of the tracking procedure, a single base stimulus and an associated initial stimulus were selected. The longer rise time of the initial stimulus was chosen to be about four times the jnds estimated by van Heuven and van den Broecke (1979). A new stimulus was chosen by the rule which decreased step size after two correct responses, but increased it after one wrong response, resulting in a correct level of performance at 0.707. For the first five reversals in a run, a 10-ms step size was used and then decreased to 3.3 ms. After two test reversals, the jnd was estimated from the mid-run average of the next ten reversals. On the average, one jnd estimate involved about 60 trials.

Stimulus presentation and response collection were under the control of a PDP-11/34 computer. Subjects ran individually in approximately 1-h sessions. A new random order of presentation for each of the eight base stimuli was used each day. Subjects were tested daily until the jnd estimates stabilized according to the criteria that no extreme estimates were obtained for that day. The experimental data were then collected on the next four consecutive days. Three of the four subjects ran for a total of eight days, the fourth subject ran for nine days. Thus four jnd estimates were collected for each base stimulus from each subject.

B. Results: Jnd estimates for each of the four subjects are plotted in Fig. 3 as the difference in rise time (Δ RT) for each base stimulus. Δ RT was calculated from each trial as the difference between the base stimulus rise time and the mid-run average rise time. Going from left to right in Fig. 3, the first panel displays the mean of the Δ RT values, the second panel the median, and the third panel the range of the maximum and minimum Δ RT values obtained. Each panel shows a clear overall trend of increasing values of Δ RT as rise time increases. Individual subject differences can be observed but they are not excessive given

the modest amount of training prior to data collection. The wide range of Δ RT values indicates that rise time discrimination in this task was difficult for subjects, particularly for long duration rise time stimuli. Since subjects occasionally produced extreme values in the tracking procedure, the median discrimination functions are probably a better estimate of rise time jnds in this experiment than the mean functions.

Combined median functions for the four subjects are shown in Fig. 4. The slight decrease in Δ RT from 10–30 ms of about 1.3 ms is less than the step size of 3.3 ms between stimuli and was contributed primarily by one subject, JL. The drop in Δ RT at 80 ms for the median function was also contributed by only one subject, SG. Considered together, these functions clearly show that subjects discriminated rise time differences well at short rise time durations, whereas they did much more poorly and displayed larger amounts of variability at longer rise time durations.

If Weber's law is applicable to rise time discrimination, then the Δ RT function should closely approximate a straight line, as indicated by a high linear correlation of $r = 0.88$. The Weber fraction calculated as Δ RT/rise time is displayed in the right-hand panel of Fig. 4. This function is typical of discrimination data obtained for simple auditory dimensions and other sensory continua where the Weber fraction is large at short stimulus values and then becomes constant over a wide range of longer stimulus values (Gescheider, 1976).

C. Discussion: The jnds estimated directly in the adaptive tracking procedure demonstrate that the discrimination of rise time follows predictions derived from Weber's law. Our results are in good overall agreement with those reported recently by van Heuven and van den Broeke (1979) who estimated jnds indirectly from standard deviations obtained using the method of adjustment. The main difference in the results between the two studies occurred for base rise time values between 10 and 30 ms. In our data, Δ RT was fairly constant in this range while van Heuven and van den Broeke reported increasing Δ RT values. On the other hand, the Weber fractions derived from Δ RT gave similar shaped functions for both sets of data over the entire 10- to 80-ms range. As discussed below, the apparent difference in Δ RT for small RT may be due to the differences in step size between stimulus pairs.

Although we found results that supported predictions derived from Weber's law, our experiment was arranged to include several high-uncertainty task variables. For similar task variables, Sachs and Grant (1976) have reported non-monotonic, V-shaped functions for measuring the jnd of voice onset time. In the present experiment, only one subject, JL, produced a V-shaped function. As a partial check on the influence of task uncertainty and to examine subject strategies, we asked subject JL to return so we could measure the jnd for the 10-ms rise time stimulus in a blocked, low-uncertainty test at the end of the experiment. Our measurement of her Δ RT fell from approximately 12 to 5 ms. Apparently this subject used a different listening strategy for the "thumpy" stimuli in the high- versus low-uncertainty tasks (cf. Gershuni and Zaboieva, 1962; Vigran *et al.*, 1964; Nabelek, 1965). Thus some of the variability obtained in our Δ RT estimates may be attributable to both task uncertainty and subjects' listening strategies.

Given the outcome of experiments 1 and 2, we wanted to account for the categorical-like discrimination results Cutting (1982) obtained with an equal interval logarithmic continuum. Therefore, we sought to develop a method for directly comparing the results from the equal logarithmic and equal linear increment continua by referring to the underlying psychometric function. The next experiment was designed to specify the relation between functions obtained in the ABX and adaptive tracking procedures.

III. EXPERIMENT 3: A COMPARISON OF DISCRIMINATION FUNCTIONS

All four subjects who ran in the adaptive tracking task of experiment 2 were recalled after four weeks and asked to participate in both the identification and ABX tasks used in experiment 1. While these subjects were experienced listeners of rise time stimuli, they were not familiar with the pluck and bow labels used in the identification testing. A warmup sequence of ten presentations of the 0- and 80-ms stimuli with feedback was used to acquaint these subjects with the pluck and bow labels. Otherwise, the same methods used for experiment 1 were used here.

A. Results and discussion

Identification and ABX discrimination functions averaged over the four subjects are presented in Fig. 5 using the same format as for experiment 1. The identification functions shown here are similar to but slightly noisier than those observed in experiment 1 (see Fig. 1). All four subjects, however, were able to categorize the endpoint stimuli as plucks or bows 100% of the time with reasonably sharp crossovers between the response categories.

The individual ABX discrimination functions revealed a great deal of subject-to-subject variability similar to those in experiment 1 (see Kewley-Port and Pisoni, 1981). The average function is shown in Fig. 5. This function is different from the ABX functions obtained in experiment 1 (Fig. 2) having more inflections and higher levels of discrimination for the longer 30- to 70-ms stimulus pairs. Nonetheless, there is a strong linear component to the discrimination function with $r = -0.84$. As shown clearly in Fig. 5, the predicted ABX discrimination function does not resemble the observed function. Thus-the ABX discrimination function is consistent with the Weber's law interpretation we gave in experiment 1.

A comparison of the ABX discrimination results with the jnd estimates obtained for the same subjects can be made by interpreting the results from each experiment in terms of the underlying psychometric function. We may reasonably assume that psychometric functions for rise time are similar to those of other auditory signals and resemble the usual ogive shape obtained when percent-correct response is plotted as a function of ΔRT (see Levitt, 1971 and Gescheider, 1976). We have approximated the psychometric function by a straight line in the range of 55%–95% correct responses, where chance is 50% correct. A predicted ΔRT for rise time can then be calculated from the percent-correct response in ABX discrimination task when the percent-correct response lies on the linear portion of the psychometric function. The equation for computing this straight line is

$$p = a \cdot \Delta RT + b, \quad (1)$$

where p is percent correct. In the ABX task, the ΔRT for each discrimination pair was held constant at a 20-ms step size and a percent-correct response was obtained. In the tracking procedure, the percent-correct response was held constant at 70.7% correct and a ΔRT was obtained. Thus we may obtain an estimated ΔRT in the ABX task at the 70.7% correct level of performance by solving the two simultaneous Eqs. (1) in terms of the intercept b . The result is Eq. (2) where the slope of the psychometric function a is still a parameter and p is the obtained percent correct in the ABX task.

$$\Delta RT_{\text{pred}} = 20 + (70.7 - p)/a. \quad (2)$$

While the slope a was not determined in these analyses, some reasonable bounds on the values it can take may be estimated from data obtained in experiment 2. A slope of 1 means

a percent-correct increase by 1% for each increase in Δ RT of 1 ms. This shallow slope implies that an additional Δ RT of 25 ms would be necessary to go from 70% correct on the psychometric to 95% correct. Referring to the functions displayed in Fig. 3, it is obvious that 25 ms is too large. A value of 5, on the other hand, is better but still too steep. If we pick an intermediate value for a , e.g., $a = 3$, this will allow us to solve for Δ RT_{pred} in Eq. (2). Although the slope of the psychometric function probably become shallower at longer stimulus durations, we will set a to a constant here.

Figure 6 shows three estimates of Δ RT as a function of rise time. From the adaptive tracking procedure, the median function from Fig. 4 is plotted as the best estimate of rise time discrimination. Plotted for the same four subjects are the Δ RT_{pred} values calculated from the ABX results using Eq. (2), labeled ABX, $N = 4$. For further comparison, the Δ RT_{pred} values for subjects in the ABX after ID procedure from experiment 1 are also plotted, labeled ABX, $N = 15$. The 70-ms point was dropped on the $N = 15$ function because ABX performance was only 53% correct.

The shape of the predicted and obtained Δ RT functions from the four experienced listeners are remarkably similar, although they are displaced from each other by about 12 ms. The Pearson product moment correlation coefficient r was used to assess whether the shape of two functions is similar. In this case, we interpret r^2 in percent to mean the extent to which the shape of one function, as measured by its variance about its mean, can be predicted from the other function. The Δ RT_{pred} function correlated with the median function from the same four subjects had an $r = 0.85$ and $r^2 = 0.72$. That is, 72% of the variance of the Δ RT_{pred} curve in the ABX experiment can be predicted from the shape of the median function. The correlation of the Δ RT_{pred} values for the two ABX functions from 10–60 ms was $r = 0.92$ indicating that 84% of the shape of one function is predictable from the other. Furthermore, the correlation r of the ABX, $N = 15$ function with the median function was also high at 0.89. Taken together, this analysis demonstrates the strong relation between the overall shape of discrimination functions obtained from the ABX paradigm and the adaptive tracking method of estimating Δ RT. We assume that this is true, in part, because the adaptive tracking task was biased towards higher stimulus uncertainty conditions making it more similar to the high uncertainty ABX task. Nevertheless, the two sets of data reveal the same underlying function.

We can now consider how estimating the slope a as a constant equal to 3 in Eq. (2) affects the above results. Varying a between 1 and 5 as a constant in Eq. (2) will only change the spread of the Δ RT_{pred} values about the mean of the function, and therefore will *not* affect the Pearson r . On the other hand, if a were decreased as rise time increased to model the usual trend of the psychometric function becoming more shallow, the Δ RT_{pred} values for longer rise times would become larger. In this case, the shape of the Δ RT_{pred} function would more closely resemble the median function and the correlations between the two sets of data presented above would improve.

While good correlation between results from the ABX and adaptive tracking procedure was obtained in this experiment, different results have been found by Burns and Ward (1978) who report labeling and discrimination data of musical intervals by trained musicians. Categorical perception of musical intervals was found in the ABX task. Asymptotic performance in the same adaptive tracking procedure used here gave a rather flat function which did not correlate with the ABX functions. These results, along with those of Carney *et al.* (1977), seem to indicate that categorical ABX functions from a high uncertainty task may *not* be observed in a low uncertainty task. Our results, on the other hand, suggest that *noncategorical*, negative sloping ABX functions do correlate with results from low uncertainty tasks.

IV. REANALYSIS OF CUTTING'S LOGARITHMIC CONTINUUM

Given the above analysis for predicting jnds from the ABX task, we turn to the recent findings reported by Cutting (Fig. 4, 1982). In his experiment 3, 12 subjects listened to two different rise time continua. The first continuum had equal *linear* step sizes (16 ms) and the obtained ABX discrimination function was similar to those of Rosen and Howell (1981) and our experiment 1 (Fig. 1). The other continuum had equal *logarithmic* step sizes ranging from 3.6–10.8 ms. The obtained two-step ABX discrimination function for this continuum had a more categorical shape. While Cutting offered no explanation why the same subjects discriminated similar stimuli according to Weber's law on the one hand or a more nearly categorical basis on the other hand, we believe we can resolve this paradox. To do this, we calculated a ΔRT_{pred} for Cutting's stimuli from Eq. (2) by substituting the ΔRT step size he used in his experiments for the 20-ms step size we used. The ΔRT_{pred} for both continua are plotted in Fig. 7 as a function of the average value for the linear stimulus pairs (labeled JEC, linear) and the intermediate rise time value for the two-step log pairs (labeled JEC, log). The first pair of log stimuli and the last pair of linear stimuli were dropped from this analysis because percent-correct response fell below 55%. The ABX, $N = 4$ and the median function from Fig. 4 are also plotted in Fig. 7 for comparison.

Both the JEC linear and the log functions are nearly straight lines with linear regression correlations of 0.99 and 0.97, respectively. The JEC linear function lies on top of the ΔRT_{pred} function from our ABX, $N = 4$ experiment. The JEC log function begins with ΔRT_{pred} values midway between our two functions and then increases linearly to reach the same ΔRT_{pred} values achieved by ABX, $N = 4$ subjects. Our ΔRT functions were quite linear over the rise time range encompassed by Cutting's log continuum, such that the correlation of the JEC log function with our median function was very high, $r = 0.99$. On the other hand, the range covered by the JEC linear continuum included an inflection point on our median ΔRT function, so the Pearson r was low, 0.69. Overall we conclude that the results for both Cutting's linear and log continua are fully replicated by the findings of our experiments. Furthermore we claim that all of Cutting's results are in complete agreement with an account of rise time discrimination that is based entirely on predictions derived from Weber's law.

Since the four ΔRT functions in Fig. 7 are similar in shape, how can we account for the relative differences between these functions? One reasonable explanation lies in the step size between the rise time stimulus pairs. In the tracking procedure, the step size was 3.3 ms. In our ABX task, the step size was 20 ms while in Cutting's linear task it was 16 ms. The variable step sizes for Cutting's logarithmic stimuli ranged between 7.9 and 19.7 ms. Results shown in Fig. 7 show that the ΔRT_{pred} functions for the 20- and 16-ms step sizes overlap. The JEC log function achieved similar ΔRT_{pred} values for the last two log pairs having rise time step sizes of 16.4 and 19.7 ms. The rapidly increasing ΔRT_{pred} values for the short rise time pairs suggests the existence of a family of functions for ΔRT which falls between the median function (at 3.3 ms) and the ABX, $N = 4$ function (at 20 ms) according to the step size used in the experiment. This account also provides a firm basis for explaining the differences in jnds between our results and those reported by van Heuven and van den Broeke (1979). Specifically, they obtained an increasing ΔRT function for rise times less than 30 ms, whereas our function was flat. Since these investigators used a 1-ms step size and we used a longer 3.3-ms step size, a floor effect may have resulted in a constant ΔRT for our small rise time values.

We propose that the categorical shape of Cutting's ABX function for logarithmically spaced stimuli arises from the unequally spaced stimuli in which the logarithmic interval was chosen arbitrarily without knowledge of the underlying Weber's constant. In Cutting's

experiment, rise time differences are below the Δ RT needed for discrimination except for a few points in the middle of the continuum. This interpretation is in accord with the interpretation given by Miller *et al.* (1976) and Pastore *et al.* (1977) that categorical perception may be observed with a continuum of stimuli which cross a sharp sensory threshold.

V. CONCLUSIONS

Several conclusions can be drawn from the present set of experiments on rise time discrimination. First, the discrimination of rise time differences for sawtooth waveforms appears to be typical of discrimination of differences for other sensory continua—the discrimination follows predictions derived from Weber's law. In this study, we showed that an interpretation based on Weber's law can be derived from ABX discrimination results as well as by directly estimating the jnds of rise time with an adaptive psychophysical testing procedure. While Rosen and Howell (1981) and, to some extent, Cutting (1982) presumed that Weber's law should imply negatively sloping ABX discrimination functions, we believe the results of the present study have now clearly demonstrated this to be the case. An interpretation of the ABX discrimination functions in terms of predictions based on Weber's law is important because the ABX paradigm is often used to compare speech and nonspeech continua for the purpose of determining natural sensitivities in the auditory system (cf. Stevens, 1981). In the past, if the ABX discrimination functions were monotonic and did not show the predicted discrimination peaks and troughs suggestive of categorical perception, no specific alternative explanations of the discrimination of the stimuli were proposed. Now it is clear that negatively sloping ABX functions are evidence that Weber's law holds for the underlying sensory discrimination being examined.

Finally, we wish to re-examine Cutting's (1982) remarks concerning categorical perception. We disagree with Cutting's claim that categorical perception as assessed by identification and ABX paradigms is a "fickle" phenomenon which may "appear and disappear" in curious ways as task variables are manipulated experimentally. The effects of stimulus uncertainty (Sachs and Grant, 1976; Carney *et al.*, 1977) and memory load (Fujasaki and Kawashimi, 1970; Pisoni, 1971, 1973, 1975) in speech sound discrimination are reasonably well understood at this time. An analysis of discrimination in the ABX paradigm and its relation to performance in other discrimination paradigms has been undertaken as well by Macmillan *et al.* (1977). Cutting's remarks about the relations between identification and discrimination were directed primarily to difficulties in interpreting his recent results with logarithmically based stimuli. While his initial analysis of the ABX discrimination results for the log stimuli appeared categorical, our reanalysis of his data demonstrated that the peaks in the discrimination functions were directly related to the unequal rise time intervals he selected in generating his stimuli. Thus contrary to Cutting's remarks, the present experiments demonstrate that when careful attention is given to stimulus preparation and task variables, the ABX paradigm is a valid and useful method for measuring discrimination of sensory continua, whether speech or nonspeech, and for making comparisons between various continua.

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FIG. 1.

Group results from the identification and ABX tests for subjects trained in using the “pluck” and “bow” labels before ABX discrimination. The identification function is plotted as percent of pluck responses. The ABX obtained and predicted functions are plotted as percent-correct discrimination (see text).

FIG. 2.

Group results from the ABX task plotted as percent-correct discrimination. The left panel shows the results from block 1 and block 2 for subjects in the ABX only condition. The right panel compares block 2 of the ABX only results with the ABX after ID results shown in Fig. 1.

FIG. 3.

Estimates of the jnds for rise time (ΔRT) as a function of rise time for each of four subjects in experiment 2. The panels display the mean, median, and range of ΔRT values for the four subjects estimated in the adaptive tracking procedure (see text for details).

FIG. 4.

Averaged results for the medians shown in Fig. 3. The left panel shows the ΔRT median function and its associated regression line; the right panel displays the Weber fraction calculated from the ΔRT median function as $\Delta RT/RT$.

FIG. 5.

Group results for the four experienced listeners for the identification and ABX tasks. Data are plotted in the same way as in Fig. 1.

FIG. 6. Predicted values of ΔRT calculated from Eq. (2) are shown for the ABX after ID results from 15 naive listeners (see Fig. 1) and the four experienced listeners (see Fig. 5). The ΔRT median function for the same four experienced listeners (see Fig. 4) is also shown here for comparison.

FIG. 7.

Predicted values of ΔRT calculated from Eq. (2) are drawn in solid lines for results reported by Cutting (1982) for two rise time continua. The filled squares show results for a continuum with equal *linear* increments whereas the open circles display the results for a continuum with equal *logarithmic* increments. The two ΔRT functions from Fig. 6 are redrawn with dashed lines for comparison.