Auditory discrimination of rise and decay times in tone and noise bursts

V. J. J. P. van Heuven and M. P. R. van den Broecke

Rijksuniversiteit Utrecht, Fonetisch Instituut, Oudenoord 6, Utrecht 2506, The Netherlands
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There are indications in the literature on speech perception that differences in rise and decay times of the amplitude envelope are relevant physical correlates in phonemic contrasts. Yet, little is known about the perception of rise and decay times as such. In the present study we have attempted to establish JND's for both rise and decay times of 1000-Hz sine waves as well as white noise bursts by means of an adjustment method. The rise and decay of stimulus amplitude were synthesized to be linear functions of time. Results show that the JND for a change in rise/decay time is generally about 25% of the duration of the rise/decay time. This Weber fraction is a minimum at rise/decay times of about 80 ms and increases significantly for rise/decay times below 20 ms. Of the four signal conditions (rise versus decay, sine wave versus noise), discriminations of decay time in noise bursts were performed with the greatest accuracy (at moderate rise/decay times), while changes in onset time of sine waves were discriminated best at very short rise times (where energy splatter may have contributed an additional cue).

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INTRODUCTION

In the physical world, no sounds occur with an indefinite duration. Any sound will thus have a beginning and an end. Moreover, it takes a certain amount of time for a sound to reach its full amplitude or, alternatively, to terminate. Yet, surprisingly little is known about the perceptual relevance of differences in rise and decay time of the amplitude envelope of sound signals, both in speech and nonspeech sounds.

This is understandable when one realizes how problematic it is to isolate the various possible perceptual correlates of differences in onset and offset in the acoustic signal (cf. Duifhuis, 1969, for pitch correlates; Landercy, 1971; Ronken, 1971, for spectral widening; Vigran, Gjaevenes, and Arnesen, 1964, for loudness; Kryter and Pearsons, 1963, for duration).

At present it is not known how large the differences in onset and offset values of acoustic stimuli have to be in order to be perceptually different or to what extent the difference limen is a function of the rise/decay time of the reference stimulus. Equally, little is known about possible perceptual differences between onset and offset durations or about the contribution of the spectral composition of the signal to the perception of differences in the onset and offset of its amplitude envelope.

Some scattered observations on rise/decay times of speech sounds may be of interest in this context; Cohen, Slis, and 't Hart (1963) found that in acceptability tasks on vowel-like sounds, Dutch, French, and American native speakers showed differential preferences for different onset times. It also appeared that very steep onsets resulted in the perception of glottal stops by French speakers, whereas relatively gradual onsets yielded /h/ perception. Malécot (1975) made similar observations for the French glottal stop, which seems to be characterized prevocalically by a short onset of, particularly, F_2 and F_3. In the final position, vowel shortening and fast offset proved to be additive cues, whereas the characteristics of initial and final positions are combined for intervocalic stop perception.

Another contribution of rise/decay times to speech perception has been suggested in systematic differences between fricatives and affricates, where affricates invariably show a shorter onset (Cutting and Rosner, 1974). Apart from onset slope, duration of the noise burst also seems to play a role in the perception of fricatives versus affricates (Cohen, Schouten, and 't Hart, 1962). The contribution of differences in rise/decay time to the perception of these categories of consonants has not been studied systematically. Cohen, Slis, and 't Hart (1963) also established that decay time rather than total stimulus duration, is primarily responsible for the perceptual difference between short, half-long, and long isolated vowels in Dutch. Differences in onset of the vowel also seem to play a role in voiced/voiceless oppositions between postvocalic fricatives in Dutch (Debrock, 1977) and between postvocalic plosives in Danish (Fischer-Jørgensen, 1963).

Prior to an investigation of the perceptual cue value of rise and decay times in a linguistic context, we needed to establish the JND of such phenomena in nonspeech sounds, such as sine waves and white noise, functioning as a baseline, and thus allowing comparison with rise and decay times in speech sounds.

I. EXPERIMENT 1

A. Method

From various techniques described in the literature, we selected the method of average error (cf. Corso, 1970), also called the method of reproduction or the method of adjustment.

The reason for this choice was that it turned out to be impossible to preserve clearly distinguishable differences in rise and decay times of amplitude envelopes on tape. We therefore decided to generate our stimuli in "real time," opting for the most efficient experimental technique available within our framework, which is the adjustment method.

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1. Subjects

Eight subjects, seven males and one female, aged between 22 and 35, staff or graduate students at the Universities of Utrecht and Leyden, participated in the experiment. They took part on a voluntary basis and were not paid. All subjects worked, studied, or had studied in the field of experimental phonetics and were aware of the purpose of the experiment. All subjects were known to have normal hearing.

2. Stimulus material

Each subject matched 148 stimuli. The total set comprised four blocks of 37 stimuli; each block consisted of five items included to familiarize the subjects with the listening condition, followed by 32 true stimuli. The four blocks of stimuli were the results of combinations of two variables: position—per block, either rise or decay time varied; signal—the source signal to be gated was either a 1000-Hz sine wave (Krohn Hite 5300 function generator) or white noise (General Radio 1382). Per block, rise and decay times of the signal were sampled at 16 points on a continuum from 0 to 100 ms, which amply covers the range of rise/decay times commonly found in speech signals. Sampling points were chosen at 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, and 100 ms. Absolute steepness did not occur at the zero setting, but was in fact approximated as closely as 15 s. The invariant slope of the signal was fixed at the midpoint of the range, i.e., 50 ms. The steady-state portion of the stimuli lasted 400 ms. The rise and decay of the amplitude envelope were linear functions of time.

Since the auditory system bases loudness judgments on log ratios, it may be the case that a nominal 100-ms linear rise time is psychologically much shorter than, e.g., a 100-ms exponential rise. However, some pilot experimentation did not clearly confirm this. Most speech sounds do not clearly show linear rise or decay time amplitude envelopes, but extensive analysis of a variety of speech sounds in various languages is needed to find out which nonlinear function approximates the onset and offset characteristics of speech sound envelopes most closely. For simplicity reasons, and moreover to allow comparison with the results obtained by Cutting and Rosner (1974), we opted for their experimental procedure in restricting ourselves to linear functions only.

A particular rise/decay time is defined as the time needed for the amplitude of the signal to reach its full level or, alternatively, to decrease to zero amplitude.

Tone and noise bursts were gated from continuous source signals by means of Grason Stadler 1287B electronic switches, which were slightly modified in order to allow us to sample the rise/decay range in a continuous fashion, rather than stepwise (cf. van den Broecke and van der Broek, 1978). The control logic determining the opening and closing moments of the gates was provided by a Devices Digitimer D4030 programmable timer.

The pulse opening the gate also triggered the function generator to start with a positive zero crossing. Notice that in the "decay" stimuli total duration increases with decay time.[1] The series of 16 different stimuli were presented twice per block in different random order per series. Order and learning effects within and between blocks were counterbalanced in a complete Latin square design.

B. Procedure

The subjects were seated in a sound-treated booth (Amplifon GR11) and participated in the experiment in four individual sessions each, one session per block.

The subject was provided with a blind five-turn knob controlling rise or decay time (depending on the condition) of a second tone or noise burst which was identical to the stimulus in all other respects and was asked to adjust the rise or decay time of the second signal until he considered it to be identical with the first signal. Thus, angular rotation of the linear potmeter gave a constant 10-ms change for every 16° of rotation. The reference stimulus and matching signal were separated by a 1000-ms pause, and the sequence was repeated every 4200 ms until the subject indicated that he was satisfied with his match.

There were no restrictions on the number or direction of the adjustments on the part of the subjects.

In half of the trials, the subject was requested to preset the adjustable signal maximally steep (0 ms); in the other half the starting position was at the other extreme (103 ms).[2] This MOVEMENT variable was incorporated in the Latin square design.

The stimuli were presented binaurally through Sennheiser HD414 headphones at 60 dB above threshold. Threshold levels were determined binaurally prior to each experimental session. The various rise and decay times were manually set by the experimenter; both reference and matching signal were monitored on a storage oscilloscope. In addition, the rise/decay time of the matching signal was continually displayed to the experimenter on a Fluke 1000 digital multimeter in 0.1-ms readings. Only the final adjustment of each trial was noted down by the experimenter rounded off to the nearest ms.

C. Results

In Fig. 1 the total set of results are broken down for the four signal conditions only. Figure 2 presents the data accumulated over all subjects in all conditions. In all these figures, the rise/decay time of the reference signal is plotted along the horizontal axis, the adjusted slope of the matching signal is plotted vertically.

Ideally, all adjusted rise/decay times should lie on the 45° line in the plot. Although the means of the adjusted slopes vary monotonously with the stimulus slopes, there are two sources of variance from the perfect fit to a straight line.

Firstly, mean adjustments to stimuli above 70 ms seem to suffer from ceiling effects, resulting in a systematic underestimation of the stimulus.

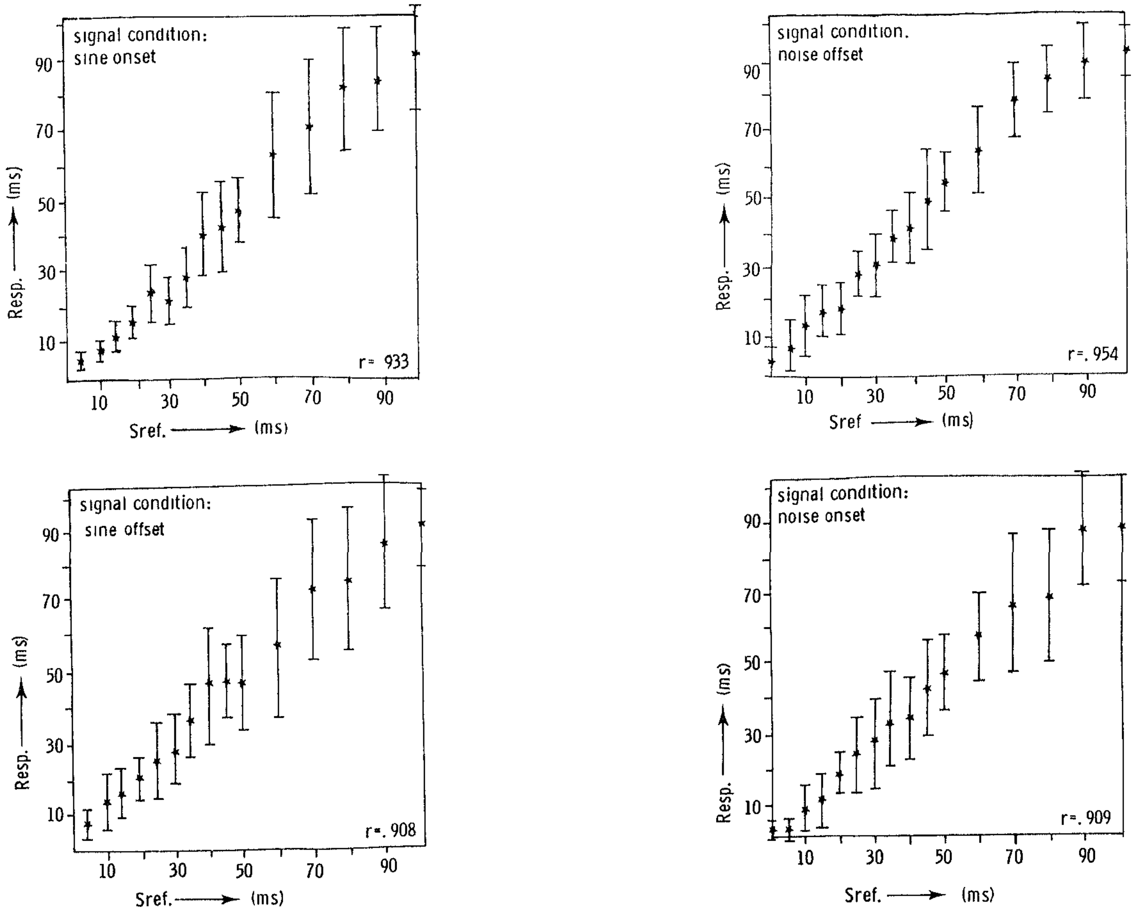

FIG. 1. Results for four different signal conditions averaged over the subject ($N=256$): adjusted rise/decay time as a function of reference stimulus duration. Standard deviations and correlation coefficients are indicated.

Secondly, there is random variation around the means of the adjustment to each stimulus type. Generally, this variance is small, as evidenced by the high correlation coefficients for the scatter in the plots, which are all above $r=0.900$.

In the plots, standard deviations around the means of the adjustments are indicated. It appears that scatter generally increases with stimulus rise/decay times.

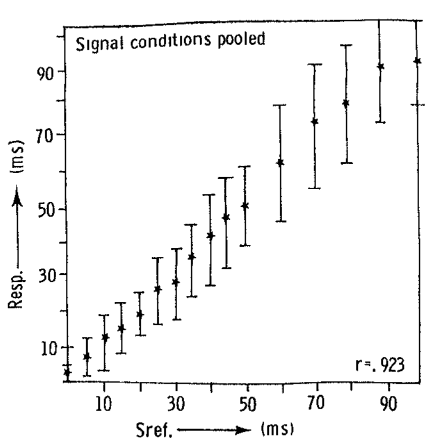

FIG. 2. Results averaged over all subjects and signal conditions ($N=1024$): adjusted rise/decay time as a function of reference stimulus duration. Standard deviations and correlation coefficients are indicated.

It should be noted, however, that only the results for stimulus types between 10 and 70 ms are relevant to this issue, as bottom and ceiling effects unduly influence standard deviations at the extremes of the range. Taking SD as a threshold measure, as can be done when there is no systematic bias in the adjustments, cf. Lopes Cardozo (1963). It is meaningful to plot SD as a function of rise and decay time of the reference signal, cf. Fig. 3.

In Fig. 3, two regression lines have been drawn, one

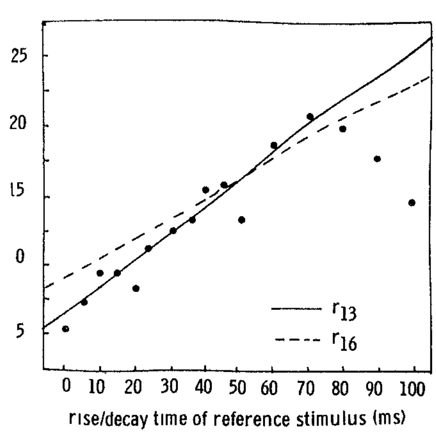

FIG. 3. Standard deviation (SD) of adjustment (as an estimate of JND) as a function of reference rise/decay time, $r_{13}=0.961$; $r_{16}=0.834$.

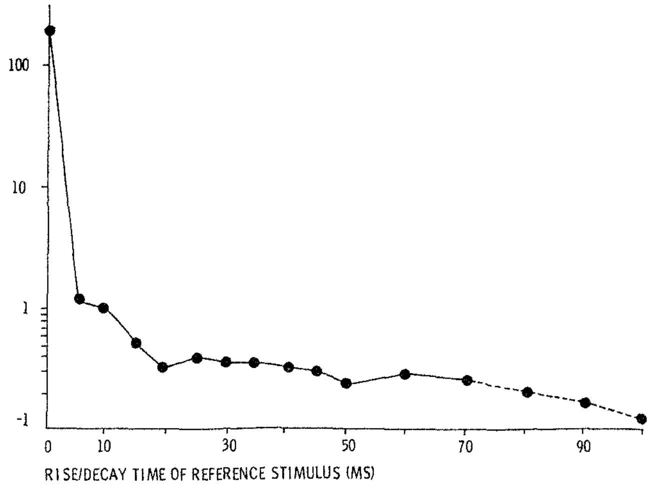

FIG. 4. Weber's ratio plotted against rise/decay time of the reference stimulus.

including and one excluding the measurement points obtained at 80–100 ms. The severity of the ceiling effect is clearly illustrated by the difference in closeness of fit of the data to the two lines ($r_{13}=0.961$, $r_{16}=0.834$). When Weber's ratio, Δ rise time/rise time, is plotted as a function of the rise/decay time of the reference stimulus, as is done in Fig. 4, it can easily be observed that the ratio remains constant for reference rise/decay times between 20 and 70 ms, after which the ceiling effect influences the results.

The sharp decrease in discriminatory ability on the part of the subjects for very short rise/decay times is in accordance with the results in the literature on auditory discrimination of duration (Small and Campbell, 1962; Henry, 1948). This means that within the 20–70 ms range, the just noticeable difference for rise/decay time is in the order of 25%.

Figure 5 gives the same information as Fig. 3, but now the four signal conditions are drawn separately. Generally, the four curves coincide, except for noise offset at reference durations beyond 60 ms, which display an accuracy on the part of the subjects that is hard to explain on the basis of the ceiling effects only.

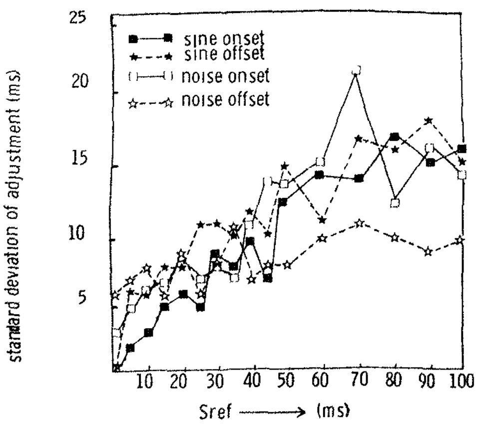

FIG. 5. Standard deviation (SD) of adjustment (as an estimate of JND) as a function of reference rise/decay time over four signal conditions.

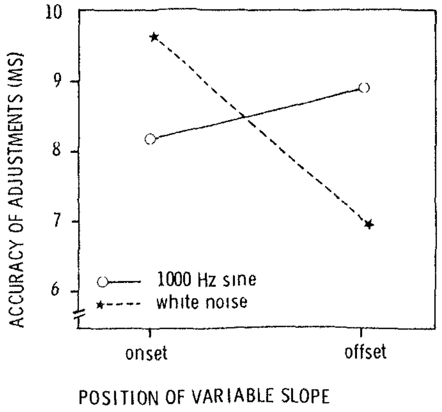

FIG. 6. Interaction diagram showing effects of position and spectral characteristics on accuracy of adjustment.

Next, we can assess whether the positions of the slope (rise time versus decay time) and the spectral composition of the gated signal (tone versus noise) are of any influence on the accuracy of the adjustment. Overall mean accuracy for each of these four conditions is given in Fig. 6.

Overall mean accuracy, defined as the absolute difference between presented and adjusted signal, amounts to 8.5 ms. Accuracy in the offset position is marginally better than in onsets (8.0 vs 8.9 ms, respectively), $F(1,1022)=3.093$, $p=0.079$. Tone signals hardly differ from noise bursts (8.5 vs 8.4 ms, respectively), $F(1,1022)<1$. As is visible in Fig. 5 however, there is some interaction between signal and position, $F(1,1020)=10.957$, $p=0.001$, in the sense that within onsets tone signals are responded to a little more accurately than noise signals (8.1 vs 9.7 ms, respectively), $t(510)=-2.03$, $p=0.043$, whereas the reverse is true in offset position (8.9 vs 7.0 ms for tones and noise signals, respectively), $t(510)=2.69$, $p=0.007$.

Within sines, onset versus offset values do not differ significantly (8.1 vs 9.0 ms, respectively, $t(510)=-1.04$, $p=0.298$). Within noise bursts, position does have a marked effect (9.7 ms for onset versus 7.0 ms for offset, $t(510)=3.80$, $p<0.001$).

Finally, we would like to discuss two points which turned out to be of minor importance.

Firstly, inspection of the Movement variable showed no significant effects. On the average, adjustments made from the starting point, 103 ms, and from 0 ms had an overshoot of 0.2 and an undershoot of 1.2 ms, respectively, $t(512)=-0.76$, insignificant.

Also, a classical four-way analysis of variance with movement, position, signal, and stimulus revealed insignificance for all second- and higher-order interactions involving the movement variable.

Secondly, although it was informally established that the subjects needed less time to achieve a satisfactory match per stimulus presentation over the course of the experimental sessions, which might point to learning effects, the accuracy of adjustment did not improve, $F(1,1022)<1$. Correlation of accuracy of adjustment with the order of presentation amounted to $r = 0.004$, insignificant. Correlation did not improve after log transformation of the time axis.

D. Conclusions

Subjects were able to reproduce rise and decay durations in short sound bursts with reasonable accuracy. There was no systematic under or overestimation in the matching task, and inaccuracy of adjustment was a linear function of the base rise/decay time. An estimation of the JND on the basis of the SD of the adjustments was about 25% of the reference rise/decay time. Accuracy of adjustment does not systematically differ for either tone versus noise signals or for onset versus offset positions. However, adjustments to tones in onset positions and to noise bursts in offset positions, were superior to the remaining combinations. No learning effects were observed. Although individual performance is quite reproduceable, subjects showed some individual differences over the four conditions.

E. Discussion

A fairly recent study using gated signals of a more complex nature, viz. sawtooth waves and naturally produced syllables beginning with fricative noise, is Cutting and Rosner (1974). In this study, using an ABX paradigm, signals varying from 1020 to 1100 ms in duration for sawtooth waves and from 410 to 490 ms for fricative noise syllables, this as a function of the rise time used (0–80 ms in 10-ms increments), were presented to 20 undergraduates as part of a course requirement. The stimuli involved in each ABX triad differed in rise time by 20 ms. Results indicate performance at or near chance level except for these pairs: 20–40 ms and 30–50 ms for sawtooth waves and 30–50 ms and 40–60 ms for syllables, where correct discrimination rose to about 75%. This is in sharp contrast with our findings which point to a much greater overall accuracy and gradual decline with increasing reference rise time (Weber's Law).

We cannot accept that the differences between these results and ours can only be attributed to differences in the source signal used, nor to differences in experimental paradigm, ABX versus adjustment method. The Cutting and Rosner stimuli were obtained by recording on audiotape, digitizing (8 kHz, 10 bits), reconverting, again recording on audiotape, and finally reproducing over loudspeakers in a partially sound attenuating room. As we noted before, reproduction of rise times on audiotape is poor and unreliable. To us, it seems likely that on-the-spot stimulus generation, as used in our experiment, is primarily responsible for the discrepancies noted.

It can be objected that our results obtained for the offset position (as well as for the onset times in the Cutting and Rosner experiments) have been influenced by interdependence of the critical variable and total stimulus duration. The majority of studies on the perception of duration (Stott, 1953; Henry, 1948; Chistovich, 1959; Creelman, 1962; Small and Campbell, 1962; Abel, 1972) seem to indicate that a perceptually noticeable increment in total stimulus duration has to exceed a minimum of 20% of the base duration, but more recent studies, conducted under optimal conditions (Ruhm *et al.*, 1966; Fujisaki, Nakamvra, and Jmoto, 1975), point to much smaller JND's for duration; thus the possibility cannot be ruled out that our results have been influenced by variations in the total stimulus duration. The argument that no principal superiority has been found for offset adjustments may, in spite of its face validity, be false in that accuracy for decay times is in fact worse than for rise times, but is raised to the same level by the additional duration cue. Therefore, a second experiment is necessary in which either the total stimulus duration will be held constant, or stimulus duration and decay time will be covaried in a two parameter study.

As a first approximation, however, we conducted a second experiment in which the steady-state portion of the gated signal was reduced from 400 to 200 ms, which means that the ratio offset duration/total stimulus duration is drastically increased. If the adjustments will turn out to be unaffected by this increase, we can safely assume that subjects are able to isolate offset duration from total stimulus duration.

II. EXPERIMENT 2

A. Procedure

In all respects except the following, experiment 2 was identical to experiment 1:

(1) The duration of the steady-state portion of the gated signal was reduced from 400 to 200 ms.

(2) The same Latin square design was used, but all subjects moved up one position in that design, so that the movement variable was reversed for each stimulus for each subject, and signal conditions and reference stimuli were presented in a different, random order as compared with experiment 1.

(3) The range of the variable resistor used by the subjects for the adjustments was increased from 103 to 110 ms to reduce ceiling effects.

B. Results and conclusions

Figure 7 presents the data accumulated over all subjects in all conditions. When plotting SD's of adjustments as a function of rise/decay time of the reference signal for the four conditions, we obtain Fig. 8. When we compare the results of the second experiment (Fig. 8) with those of the first (Figs. 1 and 2), no essential differences can be observed. A classical four-way analysis of variance, performed on accuracy of adjustment with experiment, signal, position, and duration of reference slope, showed that the variable experiment was totally insignificant, $F(1,2046) < 1$. It proved equally impossible to obtain any significant two- or higher-order interactions in which the experiment variable was involved. Thus, we can safely conclude that reduction of the total duration of the reference stimulus had no effects on the accuracy of adjustment, and therefore we can be certain that accuracy of adjustment to decaying slopes was in no way influenced by concomitant chan-

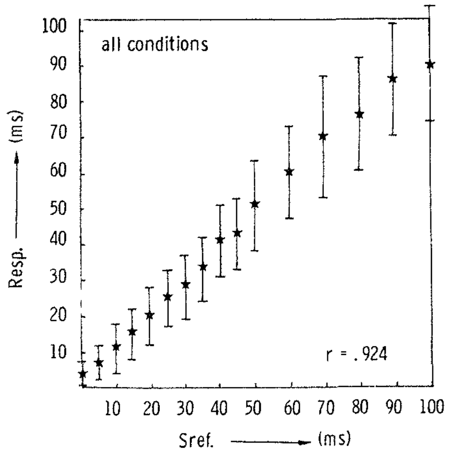

FIG. 7. Results averaged over all subjects and signal conditions ($N=1024$): adjusted rise/decay time as a function of reference stimulus duration. Standard deviations and correlation coefficients are indicated.

ges in total stimulus duration within the time range used.

Plotting SD of adjustment as a function of rise/decay time of the reference stimulus, as is shown in Fig. 9 (analogous to Fig. 3 for the first experiment), and calculating regression functions including and excluding reference stimulus durations exceeding 70 ms demonstrate that ceiling effects, which we suspected to be present in the first experiment, have now been all but eliminated. Note that the correlation coefficients obtained including and excluding values above 70 ms is the same, $r=0.974$. This almost perfect correlation indicates the applicability of Weber's law to JND's for rise/decay times. When we calculate the interactions between position and spectral composition on accuracy of adjustments, we obtain a plot as given in Fig. 10. When we compare this situation with the one obtained in the first experiment (cf. Fig. 6), we note that essentially the same interactions occur, viz. that sine onset and noise offset durations are reproduced relatively accurately, whereas sine offset and noise onset durations are reproduced relatively poorly. This is confirmed by the fact that the only significant third-order interaction in an analysis of variance of the pooled data

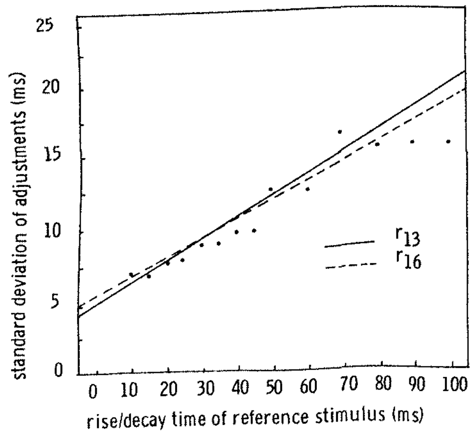

FIG. 8. Standard deviation (SD) of adjustment (as an estimate of JND) as a function of reference rise/decay time, $r_{13}=0.961$; $r_{16}=0.834$.

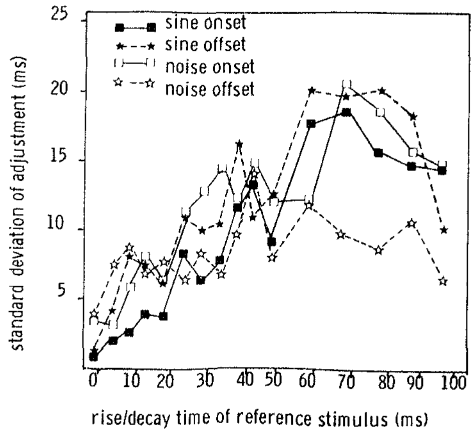

FIG. 9. Standard deviation (SD) of adjustment (as an estimate of JND) as a function of reference rise/decay time over four signal conditions.

turned out to be position×signal×duration, $F(15,1984)=1.751$, $p=0.036$.

C. Discussion

We shall now try to offer a tentative explanation for the interactions found between position and signal.

As appeared in the results, performance on sine onset and noise offset signal conditions is superior to performance on sine offset and noise onset signal conditions. A closer inspection of Figs. 5 and 8 shows that superiority of sine onsets is mainly due to accurate performance on the shorter slopes (up to 50 ms, whereas the advantage of the noise offset signal conditions is typically caused by accurate performance on the longer slopes (from 50 ms onwards). Possible reasons for these effects may be provided on the basis of the following observations:

(1) Slopes are more accurately defined in terms of their amplitude envelope for sine wave signals than for noise signals due to the inherent differences in the two types of signals. This will have more severe perceptual consequences for short durations, i.e., steep slopes. For long durations, the listener will be able to perceive

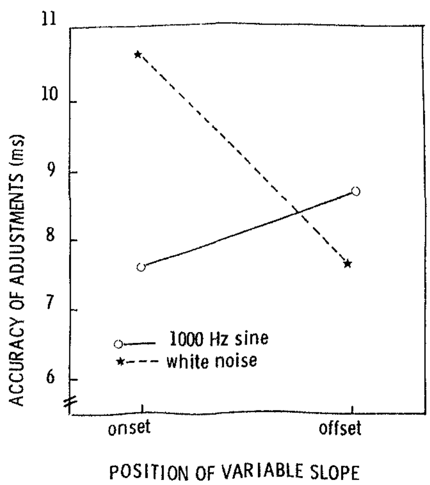

FIG. 10. Interaction diagram showing effects of position and spectral characteristics on accuracy of adjustments.

a general tendency in the changing amplitude of the signal, in spite of its moment to moment irregularities. Such a mechanism cannot operate successfully over very short time intervals, characterized by steep slopes.

(2) Well-defined sine waves are transmitted through the nervous system by a relatively small and concentrated set of receptor cells or channels, whereas information on wide-band signals, such as white noise, is transmitted through a relatively large number of disparate channels (see, e.g., Green, 1976; Moore, 1977).

(3) When tones of a well-defined frequency, such as sine waves, are presented well above threshold, auditory nerve fibres of which the center frequency equals the sine-wave frequency, will be saturated, but fibres with center frequencies further away from the sine-wave frequency need not be saturated so that they will fire in accordance with changes in the amplitude of the sine-wave frequency (Kiang *et al.*, 1965; Rose *et al.*, 1971; Evans, 1974; Siebert, 1968; Kim and Molnar, 1975; Duifhuis, 1974). This may provide an additional cue as regards the slope of the amplitude envelope in the case of sine-wave signals, which is absent in noise signals.

In view of these observations, the following consequences for the perceptibility of rise and decay times in the various signal conditions seem plausible:

(1) Sine waves are responded to more accurately than noise bursts in onset position and for short durations of the slope. Onsets of noise bursts, especially for short slope durations, are relatively hard to discriminate.

(2) In offset position, the decreasing amplitude envelope will cause a decrease in the firing rate of the fibres, which will have greater consequences when the information is transmitted via relatively few channels, as in sine waves, as compared with information, transmitted via relatively many channels, as in white noise. This will cause a relative decrease in accuracy for sine waves in offset position particularly for longer slope durations, where differences between the definition of the amplitude envelope for sine waves versus noise are not so pronounced as is the case in relatively short, steep slopes. Thus, performance on offset slopes is expected to be superior for noise as compared to sine waves.

These interpretative suggestions for the position versus signal interactions found cannot at present be quantified as their magnitude may be supposed to vary with the frequency of the sine-wave signal used. Therefore, further experimentation, using sine waves of other frequencies than 1 KHz, seems called for.

In addition, we will extend our experiments to include other than linear functions as regards the amplitude envelope of rise and decay times to assess the perceptual relevance of differences between various functions.

[1]Although it is possible to advance the closing moment of the gate in accordance with increasing decay time, thus leaving the total signal duration unaltered, this was not done for practical reasons.

[2]The five-turn variable resistor used yielded a maximum rise/decay time of 103 ms. In future experiments a wider range will be used to eliminate ceiling effects at 100 ms, cf Sec. IIB, Results.

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