Perceived Auditory Continuity with Alternately Rising and Falling Frequency Transitions*

GARY L. DANNENBRING
McGill University

ABSTRACT

Six experiments were conducted investigating perceived auditory continuity with alternately rising and falling frequency glides, in which the glides were perceived as continuous when deleted portions were replaced by white noise bursts. The first three experiments showed that perceptual continuity could be obtained when the deleted portion came either in the middle of the glide, or at the top and bottom of the glides; continuity was actually better for the latter condition. Also, it was found that as glide duration increased, the threshold between perceived continuity and discontinuity increased; there was a similar increase as the difference between highest and lowest frequencies increased. It was also found, in Experiments IV–VI, that when the peak was deleted and replaced with noise, there was no perceptual extrapolation of the incomplete glides; rather, there seemed to be considerable rounding off of the trajectory of the glide.

An interesting auditory phenomenon which has recently been investigated is perceived auditory continuity, or auditory induction (Warren, Obusek, & Ackroff, 1972). Basically, the phenomenon is one in which a soft, intermittent sound is perceived as continuous when the breaks are filled in with a louder sound. This phenomenon has been observed using a variety of stimulus materials, such as two tones of different frequencies and amplitudes (Thurlow, 1957; Thurlow & Elfner, 1959; Elfner & Homick, 1967b); soft noise bursts with loud tones as the interpolated items (Elfner & Caskey, 1965; Elfner & Homick, 1966; Elfner & Marsella, 1966; Elfner & Homick, 1967a; Elfner, 1969; Elfner, 1971); a soft tone with loud noise bursts as the interpolated signal (Warren, Obusek, & Ackroff, 1972); and soft speech stimuli with louder sounds filling in gaps in the speech (Miller & Licklider, 1950; Cherry & Wiley, 1967; Holloway, 1970; Warren & Obusek, 1971; Warren & Sherman, 1974). What all of these studies suggest is that there seems to be some sort of general mechanism which allows the auditory system to generate missing auditory stimuli under certain conditions.

One implication of studies such as that by Cherry and Wiley (1967) is that missing *formant transitions must be regenerated* for the speech to sound smooth and continuous. The importance of frequency transitions in speech has recently been emphasized by Cole and Scott (1973). They showed that when the transition in a CV syllable is removed, subjects hear the consonant perceptually segregated from the vowel. Rather than hearing a repeating CV syllable, subjects heard a repeating vowel with a consonant-like noise in the background; the CV syllable was no longer perceived as a unit. Cole and Scott suggested that the important role which frequency transitions play in speech perception is to hold the speech stream together, to prevent the sounds from becoming grouped on the basis of frequency. Bregman and Dannen-

*Experiments I–III of this research were presented at the 1974 meeting of the Eastern Psychological Association, Philadelphia, Pa., and Experiments IV–VI were presented at the 1974 meeting of the Canadian Psychological Association, Windsor, Ontario. This paper is based on part of a PH D thesis by the author. The work was supported by the following grants from the National Research Council of Canada awarded to Dr Albert Bregman: A-0127, E-3221, E-3338, and E-3413. Additional support was provided by Defence Research Board grant no. 9401–40 to Dr Albert Bregman, grants from the FCAC program of the Quebec Ministry of Education, the McGill University Graduate Faculty, and a National Research Council of Canada Postgraduate Scholarship awarded to the author. The author wishes to thank Dr Albert Bregman for his advice throughout this research.

bring (1973) have shown that frequency transitions do seem to play such a role with non-speech sounds. They found that a rapidly presented sequence of high and low tones tends to split into two streams based on frequency, a high stream and a low stream. However, adding frequency transitions between high and low tones, or adding partial transitions which merely 'pointed' at the neighbouring tones, reduced the tendency for segregation to occur, and enabled subjects to more accurately report the correct order of the tones.

Thus, it appears that frequency transitions are important in allowing the listener to correctly perceive an ongoing stream of auditory material. In addition, it seems probable that the auditory system must be able to generate frequency transitions which are missing or masked. The present studies, therefore, have been designed as a preliminary investigation of the ability of the auditory system to perceptually generate missing portions of frequency transitions. A total of six experiments were conducted. The first three experiments looked at perceived auditory continuity when the tonal stimuli were linear frequency transitions, varying the extent of the frequency change (Δf), the rate of change, and the location of the noise burst relative to the sine tone transitions. Experiments IV, V, and VI investigated the nature of the perceptually continuous signal which occurs when noise bursts are located at the top and bottom of the frequency glides. The numbering of the experiments indicates the historical order in which they were conducted.

EXPERIMENTS I–III

Experiment I was designed to investigate perceived auditory continuity with rising and falling frequency glides which had noise bursts located in the middle of each glide. In Experiment II, steady state tones were used to look at the basic effect of increasing tone duration. Finally, in Experiment III, the stimuli were again like those in Experiment I, except that the noise bursts were located at the top and bottom of the transitions rather than in the middle.

METHOD

Subjects

A total of 50 graduate and undergraduate psychology students at McGill University participated in thses experiments; all were volunteers and naive as to the purposes of the experiments. Twenty subjects participated in Experiment I, and 15 each in Experiments II and III.

Apparatus

The sine tones used in these experiments were generated by a PDP-11 computer (Digital Equipment Corp.) operating a Wavetek model 136 VCA-VCG tone generator by means of a D/A converter. To reduce switching transients in the tonal signal, all amplitude changes were made at zero voltage crossing of the signal. The white noise was generated by a Brüel and Kjær random noise generator, type 1402, and recorded on a Sony TC-200 tape recorder. The tape recorded noise was switched on and off by the computer at the proper locations in the tonal signal. The resulting tone and noise signals were combined through a microphone mixer, amplified, and presented binaurally to individual subjects through headphones. Because of various problems, different headphones were used in different experiments. The headphones used in Experiment I were Sharpe HA-8 stereo headphones; in Experiment II, Sound DH-09-S stereo headphones; in Experiment III, Koss Pro-4A headphones.

The subject adjusted a knob connected to an A/D converter, which caused the computer to modify the duration of the break in the tone (and thus the white noise duration). When the subject was satisfied with the setting, he pressed a button which caused the computer to store the value, in msec, of the duration of the white noise, and start the next trial.

Stimuli

Experiment I The stimuli for Experiment I consisted of alternately rising and falling linear frequency transitions centred at 1000 Hz and presented to subjects at 75 dB SPL, with 90 dB SPL white noise bursts presented in the middle of each glide. All dB levels were measured using a General Radio type 1551-C sound level meter with a flat plate coupler. At the offset of the tone the amplitude of the frequency transition was attenuated immediately to 12 dB for the duration of the noise burst, which was perceptually

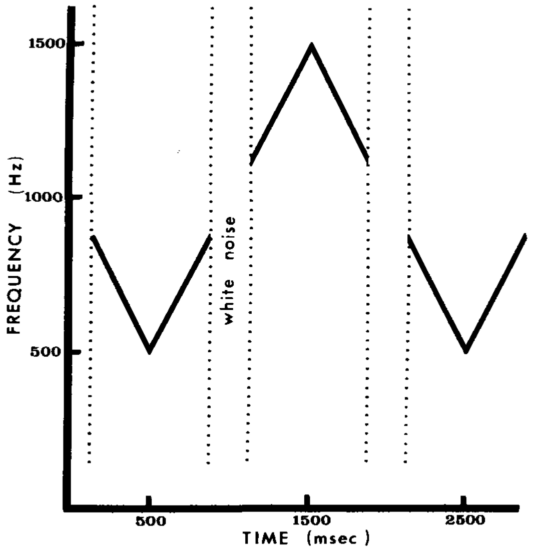

FIGURE 1 Example of a portion of a stimulus sequence used in Experiment I. In this example, Δf = 1000 Hz, and transition duration = 1000 msec.

silent. Background noise was approximately 54 dB, and consisted primarily of low frequencies, produced by the building air conditioning system. The frequency glides were produced by changing the frequency every msec, producing perceptually smooth glides; there was no perceptible 1000 Hz buzz, which one might expect due to the step-like changes in frequency. Stimuli were generated on-line, with the noise duration being controlled by the subject's adjustment of a knob. The white noise completely filled in the break in the tonal signal. Within each trial the slope of the frequency transition was kept constant, so that an increase in white noise duration caused a decrease in the duration of the audible portion of the frequency transition. A diagram of the stimuli is given in Figure 1.

Transition durations are given as the time from the middle of one white noise burst to the middle of the next noise burst; i.e., the acutal duration of the transition when the noise burst is at a minimum. Thus, with a transition duration of 500 msec, and the knob set to produce a noise burst of 100 msec, the acutal duration of the audible frequency transition is 400 msec. However, on all figures used in this paper, transition durations will be defined as stated above, or, in this case, 500 msec. There were four durations of frequency transitions: 250, 500, 1000, and 2000 msec, and four levels of the extent of frequency change (Δf): 100, 250, 500, and 1000 Hz, for a total of 16 different trials. The subject's knob was calibrated to produce white noise durations of 2–1000 msec. Since not all of the frequency glides were that long, the maximum white noise durations that the subject could make were 200, 450, and 950 msec for frequency glides of 250, 500, and 1000 msec respectively. The 16 different trials were presented in blocks three times, in a different random order for each block, for a total of 48 trials. There was also a .5 sec 2000 Hz warning tone at the beginning of each trial.

Experiment II The tonal stimuli used in this experiment consisted of a 70 dB steady-state sine tone of 1000 Hz, with 85 dB white noise bursts presented during the breaks in the tone. These breaks came, as in Experiment I, at regular intervals of either 250, 500, 1000, or 2000 msec, with the duration of the break, and thus the white noise, being controlled by the subject's knob. There were, therefore, a total of four different trials, which were presented at random 12 times each, for a total of 48 trials.

Experiment III The stimuli used in this experiment were basically the same as those used in Experiment I, except that the noise bursts occurred at the high and low points of the frequency transitions. A diagram of a portion of one of the sequences used in this experiment is given in Figure 2.

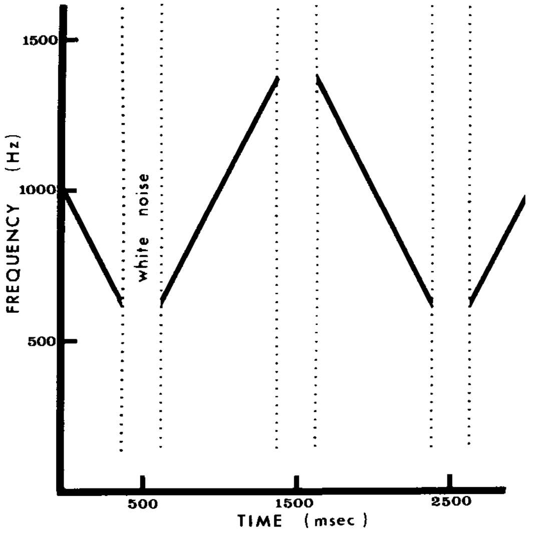

FIGURE 2 Example of a portion of a stimulus sequence used in Experiment III. In this example, Δf = 1000 Hz, and transition duration = 1000 msec.

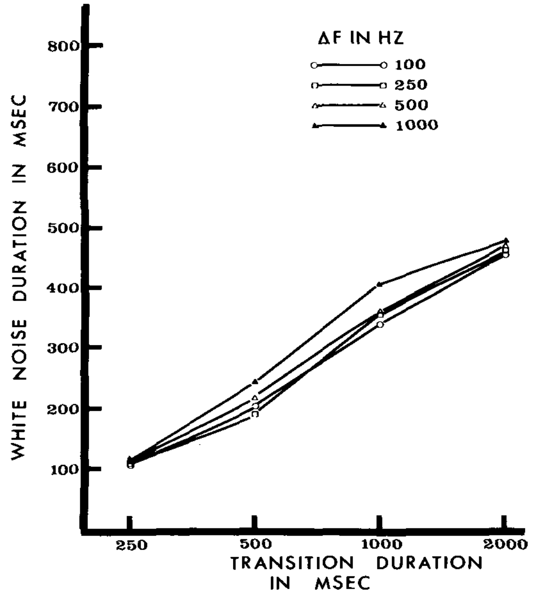

FIGURE 3 Mean continuity thresholds for Experiment I.

Procedure

Subjects were told that the frequency glides would sound continuous for very short white noise durations, and discontinuous for very long white noise durations. They were asked to adjust the duration of the white noise to find the point at which their perception of the frequency glide changed from continuous to discontinuous, or vice versa. They were free to turn the knob in both directions, and were urged to use the full range of the knob, turning it back and forth until they centred on the point between continuity and discontinuity. This point will be referred to as the threshold for continuity. When satisfied with the adjustment, the subject pushed a button which stopped the trial and recorded the white noise duration. He then turned the knob back to the shortest white noise duration, which caused the computer to start the next trial. Thus, each trial began with the knob in this position, and the computer waited for the knob to be reset before beginning the next trial. It took most subjects approximately one half hour to complete the 48 trials. In addition, each subject was given a practice trial consisting of 1000 msec frequency glides between 1000 and 2000 Hz (in Experiment II, the tone was a steady 1000 Hz), in which he adjusted the white noise duration until the threshold between continuity and discontinuity was reached. All subjects demonstrated an ability to hear continuity of the tonal signal in the practice trial.

RESULTS

Experiment I

Mean white noise durations for the threshold between continuity and discontinuity are presented in Figure 3. The threshold at which continuity was no longer heard increased as the duration of the frequency glide increased, and the effect was highly significant, $F(3,57) = 37.35$, $p < .001$. In addition, the threshold also increased as Δf increased, $F(3,57) = 5.77$, $p < .005$. There was no significant interaction between these two effects. There was also no significant difference between blocks, suggesting that increased practice with the stimuli probably did not affect the results.

Experiment II

The mean thresholds between perceived continuity and discontinuity for this experiment are shown in Figure 4. As can be seen, the threshold increased as the duration between noise burst onsets increased, and the effect was significant, $F(3,42) = 13.06$, $p < .001$.

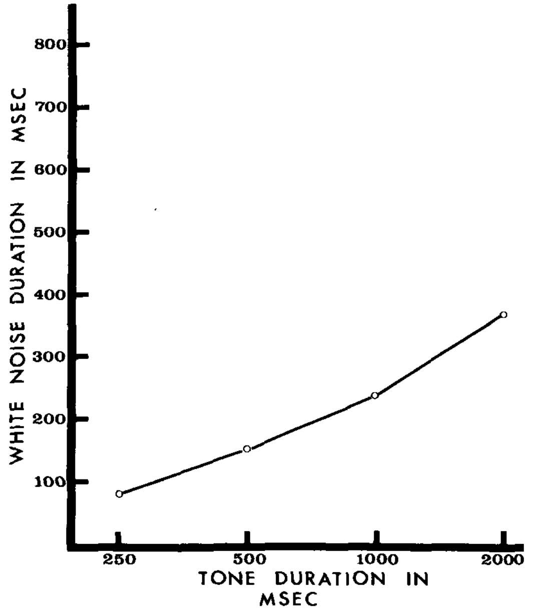

FIGURE 4 Mean continuity thresholds for Experiment II.

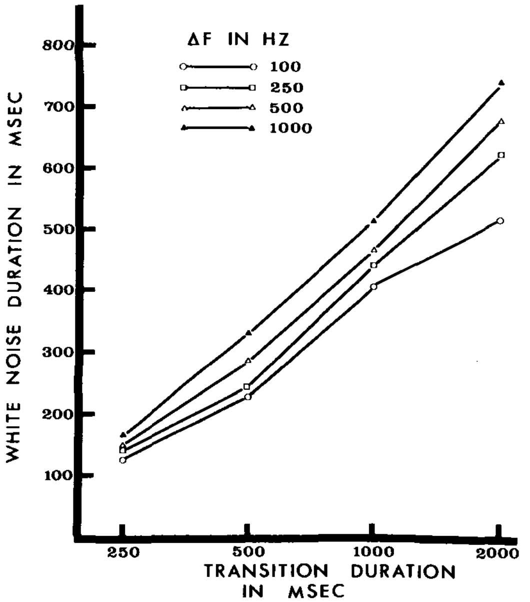

FIGURE 5 Mean continuity thresholds for Experiment III.

Experiment III

The mean white noise durations for the threshold for continuity for Experiment III are presented in Figure 5. As in Experiment I, the threshold increased as the duration of the frequency transitions increased, and the effect was highly significant, $F(3,42) = 90.46, p < .001$. In addition, as in Experiment I, the threshold increased as Δf increased, $F(3,42) = 17.88, p < .001$. There was also a significant interaction between these two effects, $F(9,126) = 3.79, p < .005$. An analysis of variance comparing the overall continuity thresholds found in Experiment II with Experiment III revealed a significant difference, $F(1,28) = 13.93, p < .001$. The mean continuity threshold for this experiment was also significantly different from Experiment I, $F(1,33) = 4.45, p < .05$. It should be noted that these tests are probably not statistically valid owing to non-random assignment of subjects to the different experiments. However, the best continuity seems to have occurred with rising and falling frequency transitions having noise bursts located at the top and bottom of the glides.

DISCUSSION

These results demonstrate, first of all, that perceived continuity occurs with frequency transitions as well as with steady-state tones, when the breaks in the transitions are filled in with white noise. Subjects perceived the transitions as being continuous over a surprisingly long break; for example, a mean white noise duration of 288 msec over all conditions in Experiment I. Similarly, Warren et al. (1972) found that subjects perceived steady-state tones as being continuous over 300 msec breaks. Elfner (1969), however, found thresholds for continuity which were less than 35 msec, even with signals as long as 950 msec. Probably the main reason for this discrepancy is that Elfner was investigating perceived continuity of soft white nosie signals with louder interpolated tones, while Warren et al., and the present study, are investigating continuity of soft tonal signals with louder noise bursts filling the spaces. Hellman (1972) found that noise masks a tone much better than a tone masks noise. Since Warren et al. (1972) have shown that masking and auditory induction seem to be related, the difference is probably due to the inability of tonal signals to efficiently mask noise in Elfner's case, and thus the inability to produce continuity of the noise signal.

A second major result was that in all experiments, the threshold for continuity increased as the duration of the tonal signal increased. This increase might be expected, to an extent, from earlier studies (Elfner & Homick, 1966; Elfner & Marsella, 1966; Elfner, 1969) which showed that continuity thresholds for noise signals slightly increased as the duration of the noise increased. However, the increase in those studies was not as great as that found in the present experiments. For example, the greatest increase was from 17 to 34 msec in one condition of the study by Elfner (1969), which was considerably less than that found in the present study. This difference could be due to the fact that the present experiments investigated continuity of a sine tone signal rather than a white noise signal, as discussed earlier.

The effect of Δf on the continuity threshold cannot be predicted from earlier work, since no previous studies have used stimuli which varied along this dimension. A possible reason for this effect of Δf is that it might reflect certain organizational principles by which the auditory system operates. Recent work by Bregman and Dannenbring (1973) suggests that the auditory system codes incoming stimuli into streams according to various 'rules' of the sensory system. They found that a rapid sequence of tones was organized into a single stream more readily when frequency transitions on the ends of the steady-state tones 'pointed' toward the neighbouring tones. It might be hypothesized that with a greater Δf there is a greater pointing effect, resulting in an increased tendency for the tonal stimuli to be included together in a single stream and thus be perceived as a continuous series of rising and falling frequency glides.

In comparing the results of Experiment I with those of Experiment III, there is a suggestion that the perception of continuity may be enhanced when the noise bursts are located at the top and bottom of the transitions rather than in the middle of them. Although it is possible that slight differences in the subject populations could be creating the different results, it is also possible that the difference is a perceptual phenomenon. It should be noted that a similar effect has been found by Glynn (1954) in a study of apparent transparency. This is a phenomenon in which, under the proper conditions, a narrow screen which is located in front of a moving rectangle appears to be transparent; i.e., subjects state that they seem to be able to see the form and colour of the object *under* the physically opaque screen. Thus, there seems to be a perceived continuity of the moving visual object, much like the perceived continuity of the tonal signal in the present experiments. Glynn found that continuity was

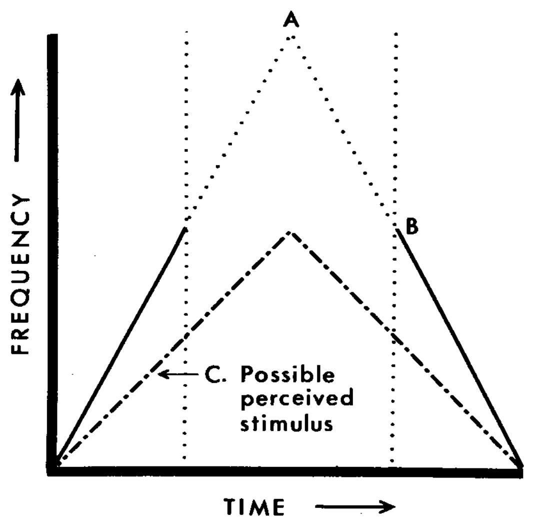

FIGURE 6 A portion of a standard sequence from Experiment IV, showing the theoretical extrapolated point and a possible perceived stimulus.

enhanced when the moving stimulus appeared to change directions somewhat while hidden by the screen, similar to the enhanced auditory continuity which seems to occur when the direction of the sine tone transition changes at the point of the noise burst.

The significant interaction between Δf and transition duration in Experiment III suggests that the effect of Δf was greater for longer transition durations than for shorter ones. However, it is not clear at this point why this occurred in this experiment and not in Experiment I. It might be noted that a scale transformation on the Y-axis, such as a square root transformation, could eliminate this interaction (Winer, 1962). Since there is no reason to assume that linear increases in the white noise duration are perceived as linear, such a transformation might be appropriate, and thus the obtained interaction may be psychologically meaningless.

Since one might expect, from the Gestalt principle of good continuation (Koffka, 1935) that linear frequency transitions should continue in a linear fashion, one might expect that subjects would hear a tonal signal in Experiment III which continues to a point that is an extrapolation of the adjacent transitions. This can be seen as point A in Figure 6. Such an expectation conforms well with the subjects informal descriptions of what they heard in Experiment III. However, some additional, informally gathered evidence suggested that this night not be the case. Rather than hearing point A in Figure 6 as the highest point, several persons, including the author, felt that point B was the highest frequency perceived. Thus, Experiments IV–VI were conducted in an attempt to determine the nature of the perceived continuous signal which occurs when the peaks of alternately rising and falling frequency transitions are removed and replaced with noise bursts.

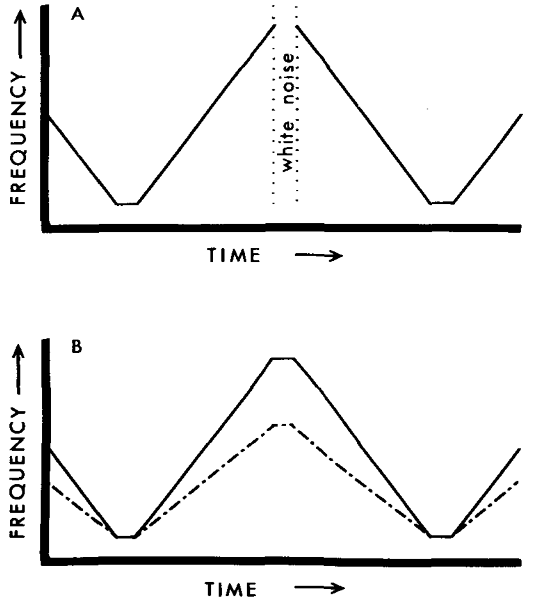

FIGURE 7 (a) Example of a portion of a standard sequence. (b) A portion of an adjustable sequence. The dashed line represents the sequence at a lower knob setting.

EXPERIMENT IV

METHOD

Subjects

Subjects were five students from McGill University. Three were graduate students in psychology, one an undergraduate in psychology, and one an undergraduate music student. All *S*s had an extensive musical background, which was the primary criterion for selecting the subjects because of the difficulty of the experiment. Two of the subjects were familiar with some of the previous work in perceived auditory continuity; however, all subjects were naive as to the purpose of the present experiment. All subjects were paid for their services.

Apparatus

The basic apparatus used in this experiment was the same as that used in the first three experiments. The headphones used in this experiment were Koss Pro-4A stereo headphones.

Stimuli and Procedure

In each trial, *S*s were presented with a standard sequence and an adjustable sequence. The standard sequence consisted of alternately rising and falling frequency glides centred at 1000 Hz, in which the upper peaks of the glides were removed and replaced with white noise bursts of either 100 or 200 msec duration. The tonal signals were presented at 75 dB SPL; the noise bursts were 90 dB SPL. The frequency glides extended the same distance below 1000 Hz as above it, with the lower portion of the glides being connected by a steady-state tone of the same duration as the white noise burst (see Figure 7). The adjustable sequence consisted of rising and falling frequency glides, as in the standard sequence, except that there was no noise burst at the peaks of the glides. Instead, the tops of adjacent glides were connected by steady-state tones. In addition, the peaks of the adjustable sequences were controlled by the subject using a knob. When the knob was in the extreme clockwise position, the peak frequency was at a minimum (the same as the lowest portion of the frequency glide), and the frequency was thus simply a steady-state tone having the lowest frequency of the standard sequence glides. As the knob was turned counter-clockwise, the peak frequency moved up. Diagrams of typical sequences are shown in Figure 7. The adjustable sequence always matched the rhythmic structure (i.e., transition duration) of the standard sequence.

In each trial, the subject was asked to first listen to the standard sequence and rate how continuous the tonal portion of the signal sounded by placing a mark on a 150 mm scale with the extremes labelled 'not continuous' and 'continuous.' Such a rating was necessary to determine whether or not subjects perceived continuity of the tonal signal in these trials. He was then asked to adjust the upper peak of the fre-

TABLE I

The results of Experiment IV, showing mean adjusted tops of the frequency glides, along with the actual tops of the standard transitions and the theoretical, extrapolated peaks.

	Noise duration					
	100 msec			200 msec		
Condition	Adjusted	Actual	Theoretical	Adjusted	Actual	Theoretical
Δf = 100 Hz						
Glide duration						
250	1026.7	1030	1050	1028.6	1010	1050
500	1041.2	1040	1050	1032.9	1030	1050
1000	1049.6	1045	1050	1046.2	1040	1050
2000	1044.4	1048	1050	1043.9	1045	1050
Δf = 250 Hz						
Glide duration						
250	1059.0	1075	1125	1024.8	1025	1125
500	1086.9	1100	1125	1062.8	1075	1125
1000	1117.1	1113	1125	1094.3	1100	1125
2000	1114.6	1119	1125	1114.6	1113	1125
Δf = 500 Hz						
Glide duration						
250	1126.2	1150	1250	1065.5	1050	1250
500	1186.9	1200	1250	1138.7	1150	1250
1000	1219.0	1225	1250	1193.4	1200	1250
2000	1246.8	1238	1250	1222.5	1225	1250
Δf = 1000 Hz						
Glide duration						
250	1246.6	1300	1500	1112.2	1100	1500
500	1380.9	1400	1500	1275.2	1300	1500
1000	1451.3	1450	1500	1374.0	1400	1500
2000	1465.1	1475	1500	1424.1	1450	1500

quency transitions of the adjustable sequence until it matched the highest point heard in the standard sequence. Each sequence was activated by holding down a switch, and subjects were encouraged to switch back and forth between standard and adjustable sequences until the adjustment was made as accurately as possible. The subject then pushed a button to record the adjusted frequency as set by the knob, and then turned the knob back to the lowest frequency, starting the next trial.

There were four different durations of frequency transitions: 250, 500, 1000, and 2000 msec, and four levels of Δf: 100, 250, 500, and 1000 Hz. All measurements are given from the lowest point of a transition to a theoretical 'peak' (point A in Figure 6). As mentioned before, there were also two white noise durations, 100 and 200 msec, for a total of 32 different trials. Subjects received these 32 trials in random order a total of four times, with 64 trials in one experimental session and 64 trials the next day. All subjects demonstrated an ability to hear continuity during 10 practice trials.

RESULTS

The adjusted peak frequencies of the adjustable sequences are shown in Table I, along with the theoretical, extrapolated peak frequencies and the actual tops of the frequency glides. This table shows that for all conditions, the frequency which the subject seemed to hear as the highest point of the standard was the actual high point of the frequency glide rather than the theoretical peak frequency. In addition, it shows that the subjects generally seem to have set the peak of the adjustable sequences slightly lower than the top of the frequency

TABLE II
Rated judgments of continuity for Experiment IV.

	Transition duration (msec)			
Δf in Hz	250	500	1000	2000
100	104	102	106	110
250	111	112	110	109
500	111	114	116	115
1000	116	119	123	123

glide. However, an analysis of variance performed on the difference scores (the difference between the adjusted frequency and the actual high point of the glide) revealed that there was no significant difference from 0.

The overall mean score made by the subjects for continuity judgments was 113. A score of 75 was the midpoint between discontinuous and continuous on the 150 mm scale. The rated continuity judgments for all conditions are shown in Table II. Analysis of variance revealed no significant main effects nor any interactions. However, all effects generally showed slight trends in the expected directions. For example, as Δf increased, the rated continuity also increased slightly, as might be expected from Experiments I and III.

DISCUSSION

The most interesting finding of this experiment was that subjects matched the high point of the adjustable sequence to the actual high point of the frequency transitions of the standard rather than to the theoretical, extrapolated peak, as had been expected on the basis of the Gestalt principle of good continuation. However, subjects generally described the tonal signal which they perceived under the white noise burst as being a peak in the frequency. Yet, it is evident from the data that the perceived peak must have been something similar to C in Figure 6 rather than the peak at A. Experiment V was designed to investigate this possibility.

Finding no significant differences across conditions for the rated continuity judgments was not totally surprising since, from the results of the first three experiments, one would generally expect subjects to hear continuity in all conditions (except possibly for transition duration = 250 msec, noise = 200 msec). In addition, there is no reason to assume that all subjects were using the same criteria in making their judgments. The important result of these ratings is simply that subjects did perceive the tonal signal to be more or less continuous through the noise burst.

EXPERIMENTS V AND VI

After finding that subjects do not perceive the gliding frequency transitions in Experiment IV as continuing beyond their actual terminal frequencies, one question which arises concerns the nature of the tonal signals which are perceived under the white noise bursts. At one extreme, subjects may have perceived something similar to C in Figure 6. At the other extreme, subjects may have correctly perceived the frequency transition until its termination, and then perceived a steady-state tone connecting the high point of one transition with the adjacent one through the white noise burst. Or, the perceived stimulus could be something between these extremes. Experiment V attempted to answer this question by having subjects modify various adjustable sequences until they matched a standard as well as possible, and then rate how well the overall structure of the perceived tonal signal of the standard matched that particular adjustable sequence.

Experiment VI was designed to investigate the perceived terminal pitch of the frequency glides in a situation in which continuity did not occur (no noise bursts were present in the standard sequences), to determine whether or not slight perceptual overshoot occurs in an auditory continuity situation.

METHOD

Subjects

Subjects were 10 psychology students (five in each experiment) who were paid for their services. All subjects had a musical background, as in Experiment IV. One subject had also participated in Experiment III; however, he and all other subjects were naive as to the purpose of the present experiments.

Apparatus

The apparatus used was the same as in Experiment IV, except that the headphones were Sennheiser HD-414 stereo headphones.

Stimuli and Procedure

Experiment V As in Experiment IV, the subject was presented with a standard and an adjustable sequence in each trial, each activated by holding down a switch. The standard sequences were the same as those in Experiment IV, except that there were only three levels of Δf: 250, 500, and 1000 Hz, and three transition durations: 250, 500, and 1000 msec. The white noise bursts were 100 or 200 msec in duration. There were five different types of adjustable sequences, the difference being in the steady-state duration at the top of the frequency glides. The steady-state duration was either 0 (a peak, or point), 25%, 50%, 75%, or 100% of the duration of the noise burst of the standard sequence. Thus, for the 100 msec white noise burst, the steady-state duration of the adjustable sequence (the duration of the tone in that sequence which corresponds to the noise burst of the standard) was either 0, 25, 50, 75, or 100 msec. For standard sequences with 200 msec noise bursts they were 0, 50, 100, 150, or 200 msec. There were, therefore, a total of 80 different trials, which subjects received twice (in 2 sessions) for a total of 160 trials.

The subject was asked, for each trial, to modify the adjustable sequence until the high point of the frequency transition matched the high point of the standard as well as possible. After the adjustment was made, the subject was asked to rate how the overall form of the adjustable sequence sounded compared to their perception of the tonal signal in the standard. Since the subject had already adjusted the frequency, any difference between the two should be due to differences in the perceived duration of the high point of the standard sequence as compared with the adjustable sequence. This rating was done on a 7-point scale with 1 being 'exactly alike' and 7 being 'quite dissimilar.' The subject was given an example of two sequences exactly alike (the 'standard' in this example did not have any noise bursts at the peaks; instead, the frequency came to a point, or 0 steady-state duration, and then came down), and was told that tonal stimuli this similar should be rated '1.' He was also given the same standard and an adjustable sequence witha 200 msec steady-state duration at the peaks, and was told that this should be a '7.' All subjects felt that they could hear definite differences between the two examples, and seemed to understand the rating procedure.

After the subject had made his rating on paper, he pushed a button which corresponded in number to his rating. This number was recorded by the computer along with the knob setting. As in the previous experiments, the subject then turned the knob back to the extreme clockwise position (the lowest frequency), and the next trial began.

Experiment VI The stimuli and procedure for Experiment VI were the same as for Experiment V, with the following exceptions: (1) there were no noise bursts in the standard sequences, only a break at the peaks of the frequency transitions, and (2) subjects did not rate the similarity between the standard and adjustable sequences, since auditory continuity was not being investigated in this experiment.

RESULTS

Experiment V

The first and most obvious result of this experiment is that, as in Experiment IV, subjects matched the adjustable sequences to approximately the actual top of the glides of the standard sequences rather than extrapolating beyond this point. This can be seen in Table III. An analysis of variance performed on the difference scores again revealed no significant differences from 0. There was, however, a considerable difference between the different comparison steady-state durations. This difference is shown in Figure 8. When the steady-state peak frequency of the adjustable sequence was 0, subjects adjusted the frequency above the actual top of the frequency glide of the standard. The adjusted value decreased in frequency as the steady-state value increased. An analysis of variance showed this to be highly significant, $F(4,16) = 44.97$, $p < .001$. The analysis also revealed a significant interaction between

TABLE III

The results of Experiment v, showing mean adjusted tops of the frequency glides, along with the actual tops of the standard transitions and the theoretical, extrapolated peaks.

	Noise duration					
	100 msec			200 msec		
Condition	Adjusted	Actual	Theoretical	Adjusted	Actual	Theoretical
$\Delta f = 250$ Hz						
Glide duration						
250	1069.3	1075	1125	1029.3	1025	1125
500	1102.5	1100	1125	1077.0	1075	1125
1000	1116.1	1113	1125	1105.3	1100	1125
$\Delta f = 500$ Hz						
Glide duration						
250	1145.3	1150	1250	1057.8	1050	1250
500	1201.5	1200	1250	1162.8	1150	1250
1000	1227.7	1225	1250	1207.7	1200	1250
$\Delta f = 1000$ Hz						
Glide duration						
250	1291.9	1300	1500	1131.3	1100	1500
500	1400.9	1400	1500	1304.2	1300	1500
1000	1452.8	1450	1500	1417.3	1450	1500

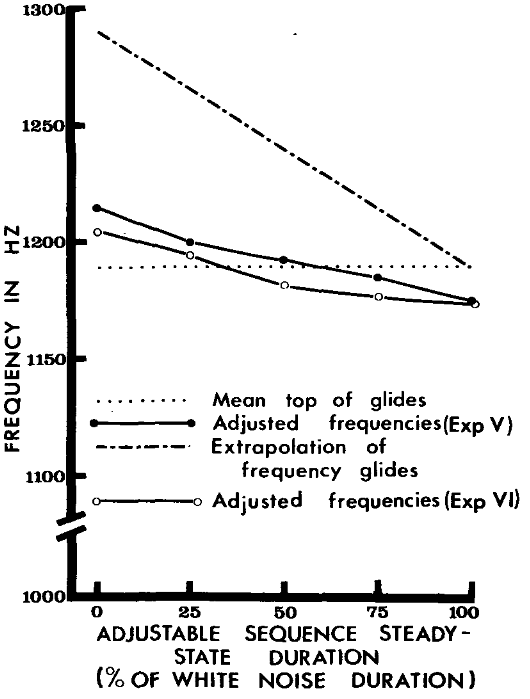

FIGURE 8 Mean adjusted frequencies of Experiments v and vi for the 5 different types of adjustable sequences, along with the actual peaks of the frequency glides and the imaginary, extrapolated points.

steady-state duration and Δf, $F(8,32) = 3.86, p < .01$ (the slope of the function in Figure 8 increased as Δf increased), and between steady-state duration and transition duration, $F(8,32) = 3.38, p < .01$ (the slope of the function decreased as transition duration increased).

The results of the rated similarity between the adjusted sequences and the standard sequences were highly ambiguous. There was no significant difference between the five percentage steady-state durations as had been expected. There was, however, a significant interaction between transition duration and steady-state time, $F(8,32) = 2.43, p < .05$, which can be seen in Table iv; there seemed to be a slight u-shaped function for a transition duration of 250 msec, while for transition durations of 500 and 1000 msec the functions are basically flat.

A part of the reason for the ambiguity of the rating data seems to be due to the fact that for certain conditions none of the adjustable sequences were very good examples of the perceived tonal signal of the

TABLE IV
Rated similarity between standard and adjustable sequences for Experiment v.
(1 = exactly alike; 7 = quite dissimilar.)

Transition duration	Steady-state duration (% of standard noise duration)				
	0	25	50	75	100
250	3.25	3.07	3.23	3.60	3.93
500	2.23	2.60	2.43	2.48	2.25
1000	2.57	2.82	2.53	2.55	2.47

standard. For example, there was a significant interaction between Δf and noise duration, $F(2,8) = 5.69, p < .05$, in which the overall rated similarity between the standard and adjustable sequences decreased for noise = 200 msec but remained the same for noise = 100 msec. In addition, rated similarity was better as glide duration increased for noise = 200 msec, but remained the same for noise = 100 msec, $F(2,8) = 48,29, p < .001$.

Experiment VI

As in Experiment v, subjects adjusted the top of the adjustable sequence above the actual top of the frequency glide for the 0% condition, and this frequency dropped as steady-state duration increased (shown in Figure 8). An analysis of variance showed this to be significant, $F(4,16) = 39.42, p < .001$. There was also a significant interaction between the adjustable sequence steady-state duration and transition duration (as also occurred in Experiment v), $F(8,32) = 2.78, p < .025$. Although the adjusted frequencies were slightly lower than in Experiment v, an analysis of variance conducted to describe the relationship between the two experiments revealed no significant difference between the two.

DISCUSSION

As has already been stated, Experiment v basically replicates the results of Experiment iv, in that subjects again matched the adjustable sequence approximately to the actual top of the standard sequence frequency glide rather than to a theoretical, extrapolated peak. In fact, glides in this experiment were adjusted closer to the actual tops of the standard glides than in Experiment iv. This was apparently due to varying the duration of the steady-state portion of the adjustable sequence, with an overshoot in adjustment when the adjustable sequence had no steady-state duration, to an undershoot for the 100% steady-state duration. This last type of adjustable sequence, of course, is the same as that used in Experiment iv, and the results are quite similar.

In addition, this experiment demonstrates that subjects did not match the slopes of the standard and adjustable sequences rather than the perceived high points. The frequencies to which the adjustable sequences would have been set, had subjects been matching for slope, are shown in Figure 8 as the extrapolations of the frequency glides. Thus, subjects were apparently doing the task required of them.

It is known from several studies (Brady, House, & Stevens, 1961; Nábělek, Nábělek, & Hirsh, 1970, 1973) that subjects perceive the pitch of a frequency transition to be some sort of average of the frequencies occurring over a brief period of time. This process would affect the perception of both the standard and comparison sequences in Experiment vi, thus making accurate measurement of the perceived end points of the standard sequences difficult. However, the importance of the results of Experiment VI is their similarity to the results of Experiment V. It seems clear that subjects in Experiment V did not hear the sine tone, which they perceived as continuous beneath the noise bursts, as extending beyond the actual end points of the frequency glides.

Very little useful information can be obtained from subjects ratings of the similarity between adjustable and standard sequences. Apparently, the adjustable sequences often never sounded similar to the standard, in spite of changes in the duration of the steady-state portion. This seemed to be especially true of the 200 msec noise condition, and resulted in several interactions described in the results. The best explanation that can be offered is that subjects may have perceived a tonal stimulus in the standard which was considerably rounded off, not the abrupt changes as in the adjustable sequences, and thus none of them may have sounded like the standard.

GENERAL DISCUSSION

The present experiments, together with the previous research investigating this phenomenon, provide a body of evidence in which a number of parameters have been manipulated, and the resulting effects upon perceived auditory continuity observed. For example, the effects of varying the frequencies of the two signals (Thurlow, 1957; Thurlow & Elfner, 1959; Warren et al., 1972), the direction in space of the two signals (Thurlow & Marten, 1962; Elfner, 1969; 1971), and the relative loudness of the two signals (Thurlow, 1957; Thurlow & Elfner, 1959; Warren et al., 1972) have all been previously investigated. In the present experiments, some of the results of interest were the effects of signal duration and Δf on perceived auditory continuity.

As was stated earlier, the duration of the softer signal has been demonstrated in previous studies to affect the threshold for continuity (Elfner & Homick, 1966; Elfner & Marsella, 1966; Elfner, 1969). The present experiments demonstrated a very strong effect of the duration of the softer signal on the threshold between perceived continuity and discontinuity; as the duration of the signal increased, the duration of the break over which continuity of the tonal signal was still perceived also increased.

The effect of Δf on perceived auditory continuity is difficult to explain. Experiments I and III very clearly demonstrate that increasing the differences between high and low points of the frequency transitions resulted in an increase in the duration of the break which can occur in the signal and still result in a perceptually continuous signal. As was suggested earlier, this may be due to an increased 'pointing' effect, resulting in an increased tendency for the stream to be perceived as an unbroken, continuous stream.

One of the most interesting results of the present study was that of Experiment III: that not only did subjects perceive continuity of the tonal signal when the peaks were replaced with noise, but that these conditions seemed to be better for perceived continuity than when the noise came in the middle of the glides, as in Experiment I. The work of Glynn (1954) on the apparent transparency effect, cited earlier, demonstrated a similar phenomenon in vision. Experiments IV, V, and VI suggested that subjects listening to these stimuli perceived a tonal signal which was not an extrapolation of the frequency glides, but rather was a continuous rising and falling tone having the upper pitch of the end points of the frequency glides.

An important question which needs to be answered concerns the reason that the auditory system organizes these tonal signals into one continuous tone rather than a tone alternating with a noise burst. The answer may be in the perceptual significance of boundaries between auditory events. In general, the most important information for the perceptual system concerns the location of boundaries between stimuli in an incoming stream. This is true even at very low levels in the nervous system (Ratliff & Hartline, 1959). However, it also may be a general principle of the perceptual system to ignore or reduce the discontinuities in the incoming signal as much as possible, especially when the discontinuities are occurring at a rapid rate.

One important principle which seems to be used in this process is that of segregating items which differ along some dimension into different streams. This is the phenomenon of auditory stream segregation. For example, rapid alternation between tones of widely differing frequencies results in extreme discontinuities in the stream of sounds, and the auditory system seems to respond to this situation by splitting the sounds into two streams based on frequency (Bregman & Campbell, 1971). Although such a procedure by the auditory system serves to reduce discontinuities in a stream of sounds, the ultimate reduction in discontinuity is when one of a series of alternating sounds is heard as perceptually continuous, the situation that occurs with auditory continuity. In fact, auditory continuity might be considered a special case of auditory stream segregation, in that the auditory system organizes the input into two streams of sound. Subjects subjective impression of the stimuli in the present experiments was generally that one of the sounds was heard as continuous, and that there seemed to be no temporal relationship between the two sounds; i.e., they seemed to form separate streams. For example, given the stimuli used in Experiments I and III, a number of persons in informal sessions have described difficulty in identifying differences between the two kinds of stimuli, despite the fact that in one case the noise burst is located in the middle of the frequency transition, and in the other case at the top and bottom of the transition. The most reasonable explanation for this is that the tonal signal forms one continuous perceptual stream, with the noise forming another stream, and thus judgments of temporal relationships between the two streams become difficult. This, of course, can possibly explain the difficulty subjects have in locating in the speech stream an extraneous sound that is replacing a phoneme (Warren & Obusek, 1971; Warren & Sherman, 1974). Similar experiments might also be conducted, using non-speech stimuli, to see whether or not subjects can make judgments of temporal relationships between the two sounds in a perceived auditory continuity situation.

Given a situation in which two objects (A and B) have a common boundary, three events are possible in the real world: (1) the boundary represents the end of object A and the beginning of object B; (2) the boundary is only a property of object A, and object B exists *behind* A; (3) the boundary is only a property of object B, with object A extending behind B. In a perceived auditory continuity situation, there is a common boundary between the two auditory events. However, the stimulus conditions suggest that the boundary only belongs to one of the auditory objects; the other object is perceptually continuous. Those conditions, as shown by Warren et al. (1972), are conditions in which one stimulus would ordinarily mask the other. The boundary then seems to be assigned to the masking stimulus, while the other, lacking a boundary, is perceived as continuous. Warren et al., however, do not seem to feel that a compensation for masking is the complete explanation for auditory continuity; they also state that contextual evidence must suggest that a sound could be present for the duration of the louder signal.

Bregman and Dannenbring (1975) have recently demonstrated such context effects using sine tones alternating with noise bursts, in which the amplitude of the tonal signal was varied just before and after the noise bursts (either increasing or decreasing linearly). It was found that when the tone suddenly gets softer before the noise, a situation in which the context is suggesting that the tone *might* turn off during the noise, continuity thresholds were considerably reduced, below the level for control stimuli having steady-state amplitudes. In addition, somewhat smaller decreases in continuity thresholds were obtained for stimuli having increases in the total amplitude before the noise. These findings have since been replicated in a more extensive, unpublished study conducted in our laboratory. It appears, then that these amplitude changes are giving the auditory system evidence that a discontinuity is probably occurring during the noise bursts, thus reducing the perception of tonal continuity.

RÉSUMÉ

Six expériences sur la perception auditive de la continuité avec pour stimuli des coulés sonores de fréquence alternativement ascendante et descendante, où les coulés sont perçus comme continus lorsqu'on en détruit certaines portions pour les remplacer par des bruits blancs. Les trois premières expériences montrent qu'on peut obtenir une perception continue quand la portion détruite intervient au milieu ou au sommet et la base du coulé, la continuité étant en fait meilleure en cette dernière condition. De plus, à mesure que s'accroît la durée du coulé, le seuil entre continuité et discontinuité augmente; la même augmentation s'observe à mesure que s'accroît la différence entre les plus hautes et les plus basses fréquences. Dans les trois autres expériences, on observe également que, si l'on remplace par un bruit le sommet du coulé, il ne se produit pas d'extrapolation dans les coulés incomplets; mais il semble plutôt qu'il se produise un adoucissement considérable de la trajectoire du coulé.

REFERENCES

BRADY, P.T., HOUSE, A.S., & STEVENS, K.N. Perception of sounds characterized by a rapidly changing resonant frequency. *J. Acoust.Soc. America*, 1961, **33**, 1357–1362

BREGMAN, A.S. & CAMPBELL, J. Primary auditory stream segregation and perception of order in rapid sequences of tones. *J. exp. Psychol.*, 1971, **89**, 244–249

BREGMAN, A.S., & DANNENBRING, G.L. The effect of continuity on auditory stream segregation. *Percept. Psychophys.*, 1973, **13**, 308–312

BREGMAN, A.S., & DANNENBRING, G.L. The effect of brief amplitude changes on perceived auditory continuity. Paper presented at the annual meeting of the Eastern Psychological Association, April 1975

CHERRY, C., & WILEY, R. Speech communication in very noisy environments. *Nature*, 1967, **214**, 1164

COLE, R.A., & SCOTT, B. Perception of temporal order in speech: The role of vowel transitions. *Canad. J. Psychol.*, 1973, **27**, 441–449

ELFNER, L.F. Continuity in alternately sounded tone and noise signals in a free field. *J. acoust. Soc. America*, 1969, **46**, 914–917

ELFNER, L.F. Continuity in alternately sounded tonal signals in a free field. *J. acoust. Soc. America*, 1971, **49**, 447–449

ELFNER, L.F., & CASKEY, W.E. Continuity effects with alternately sounded noise and tone signals as a function of manner of presentation. *J. acoust. Soc. America*, 1965, **38**, 543–547

ELFNER, L.F. & HOMICK, J.L. Some factors affecting the perception of continuity in alternately sounded tones and noise signals. *J. acoust. Soc. America*, 1966, **40**, 27–31

ELFNER, L.F., & HOMICK, J.L. Auditory continuity effects as a function of the duration and temporal location of the interpolated signal. *J. acoust. Soc. America*, 1967, **42**, 576–579. (a)

ELFNER, L.F., & HOMICK, J.L. Continuity effects with alternately sounding tones under dichotic presentation. *Percept. Psychophys.*, 1967, **2**, 34–36. (b)

ELFNER, L.F. & MARSELLA, A.J. Continuity effects with alternately sounded noise and tone signals. *Med. Res. Eng.*, 1966, **5**, 22–23

GLYNN, O.F.M. Apparent transparency and the tunnel effect. *Quart. J. exp. Psychol.*, 1954, **6**, 125–139

HELLMAN, R.P. Asymmetry of masking between noise and tone. *Percept. Psychophys.*, 1972, **11**, 241–246

HOLLOWAY, C.M. Passing the strongly voiced components of noisy speech. *Nature*, 1970, **226**, 178–179

KOFFKA, K. *Principles of Gestalt psychology.* New York: Harcourt, Brace, and World, Inc., 1935

MILLER, G.A., & LICKLIDER, J. The intelligibility of interrupted speech. *J. acoust. Soc. America*, 1950, **22**, 167–172

NÁBĚLEK, I.V., NÁBĚLEK, A.K., & HIRSH, I.J. Pitch of tone bursts of changing frequency. *J. acoust. Soc. America*, 1970, **48**, 536–553

NÁBĚLEK, I.V., NÁBĚLEK, A.K., & HIRSH, I.J. Pitch of sound bursts with continuous or discontinuous change of frequency. *J. acoust. Soc. America*, 1973, **53**, 1305–1312

RATLIFF, F., & HARTLINE, H.K. The response of limulus optic nerve fibers to patterns of illumination on the receptor mosaic. *J. gen. Physiol.*, 1959, **42**, 1241

THURLOW, W.R. An auditory figure–ground effect. *Am. J. Psychol.*, 1957, **70**, 653–654

THURLOW, W.R., & ELFNER, L.F. Continuity effects with alternately sounding tones. *J. acoust. Soc. America*, 1959, **31**, 1337–1339

THURLOW, W.R. & MARTEN, A.E. Perception of steady and intermittent sounds with alternating noise–burst stimuli. *J. acoust. Soc. America*, 1962, **34**, 1853–1858

WARREN, R.M. & OBUSEK, C.J. Speech perception and phonemic restorations. *Percept. Psychophys.*, 1971, **9**, 358–362

WARREN, R.M., OBUSEK, C.J., & ACKROFF, J.M. Auditory induction: Perceptual synthesis of absent sounds. *Science*, 1972, **176**, 1149–1151

WARREN, R.M., & SHERMAN, G.L. Phonemic restorations based on subsequent context. *Percept. Psychophys.*, 1974, **16**, 150–156

WINER, B.J. *Statistical principles in experimental design.* New York: McGraw-Hill, 1962

(First received 23 July 1975)
(Date accepted 14 April 1976)