Auditory Continuity and Amplitude Edges*

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ABSTRACT

The present experiments investigated the illusion of a soft tone sounding continuous when it was actually alternating with a burst of louder noise. It was found that brief changes in the amplitude of the tones, introduced before and after the noise burst, reduced the illusion of continuity; this reduction was greater when the amplitude decreased rather than increased before the noise. The results suggest that lack of 'edge information' is implicated in the illusion of continuity.

Perceived auditory continuity has recently been investigated by a number of researchers. This in an illusion in which an interrupted, softer sound, such as a tone, is perceived as continuous when a louder sound, such as a noise burst, fills in the missing spaces. The approach taken by most of the researchers has been to try to explain this effect by a relatively simple persistence of the neural activity related to the softer sound, which is assumed to be the result of some facilitation by the neural activation associated with the louder interrupting sound (Thurlow & Elfner, 1959; Elfner, 1971; Elfner & Caskey, 1965; Houtgast, 1972; van Noorden, 1975). Indeed, in cases where the neural response to the louder sound would be most likely to interact with that of the softer sound, i.e., where masking would be likely to occur, the illusion is better. This result was found by Warren, Obusek, and Ackroff (1972); however, it was not interpreted by them as a simple facilitation effect, but as suggesting that the perceived continuity is a way in which the auditory system compensates for masking in a situation where the louder sound really would have masked the softer one had the latter actually been continuous. The illusion is due to the operation of the same process operating in cases which merely mimic the true masking situation.

Accepting the conclusions of Warren et al. does not entail rejecting the 'neural persistence' hypothesis mentioned earlier. Perhaps simple neural persistence is the mechanism by which the auditory system compensates for masking. One is led, however, to question this assumption by a number of findings. The first is that if a phoneme in a sentence is replaced by a noise burst, the missing phoneme is perceptually restored (Warren & Obusek, 1971; Warren & Sherman, 1974). Neural persistence is an inadequate explanation. Of course, it may be that different mechanisms are involved in phonemic restoration than in restoration of missing pure tones.

An illusory continuity effect has, however, been demonstrated with pure tones in a situation where simple neural persistence is insufficient to explain the effect. If a pure tone is repeatedly and continuously gliding up and down in pitch, and parts of the glide pattern are deleted and replaced with noise bursts, the illusion of continuity is at least as good as with tones of steady pitch (Dannenbring, 1976). The missing portion of the glide, be it the rising part, the falling part, or the part where the direction of the glide is changing, is always perceptually restored. This suggests that a simple neural

*This research was supported by grants from the National Research Council of Canada, the FCAC program of the Quebec Ministry of Education, and the McGill University Graduate Faculty, awarded to the first author. Reprints may be obtained from the first author, Psychology Department, McGill University, 1205 McGregor Ave., Montreal, Quebec, Canada, H3A 1B1

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persistence model is inadequate and that the mechanism must at least be capable of pitch interpolation.

In trying to analyse a perceptual phenomenon, it is important to consider the pattern-recognition aspects of the situation. It is likely that most illusions are cases where a mechanism that produces correct description in a natural-world situation is led by an impoverished stimulus situation to create an incorrect description. Illusions are important, therefore, in determining the information used by pattern-recognition mechanisms. We are led by such considerations to reason as follows. In the real world, the input to our ears is structured by many co-occurring sound sources, often momentarily obliterating the evidence of one another's existence. The auditory system must recover from this input a description of the various individual sources. To understand this process we must ask what information can be used to effect this decomposition of the input. Speculations as to the neural mechanisms are premature until we have a clear picture of what information is used.

One source of information concerning whether a softer sound is or is not continuing behind a louder one is obvious – whether or not the neural processes corresponding to the frequency components of the softer sound continue through the louder sound. This is the source of evidence referred to in the 'neural perseveration' hypothesis. But is it only one source of evidence; another is what happens to the two signals at the edges where they meet.

We know that, in vision, what happens at an edge is critical. Two surfaces which differ in brightness at the edge where they meet, but change smoothly to equal brightnesses away from the edge, will be seen as two surfaces of different brightness, each surface being homogeneous in brightness (Cornsweet, 1970, p. 273). It is reasonable to postulate that the temporal edges in audition, for example where a soft sound meets an interrupting sound, are of equal importance, In vision, we also know that when two regions. A and B, meet at an edge, the edge is usually assigned perceptually to only one region, A, and the shape of the edge is seen as specifying only the shape of A, not of B. When this happens, the B region is seen as overlapped by A and as continuing behind A. In the analogous case of two sounds, A and B, meeting at an 'edge,' the edge is probably assigned as a property of the louder masking sound, A (for ecologically valid reasons), and as specifying a temporal boundary for A, but not for B. A is heard as overlapping B, which continues behind A. This will be particularly true if B is heard again at the offset edge of A. There is simply no independent 'edge' information left over for B, to indicate that it, too, is bounded at the junction of A and B.

Suppose however, that we did provide some edge information for B independent of the onset of the louder sound, A, so as to suggest that B was turning off. Then B should be less likely to be heard behind A. Thus if we quickly turned down the loudness of a tone by 10 dB just before a loud noise burst replaced it, and quickly turned it up again by 10 dB after it replaced the noise burst in a repeating cycle, the resultant amplitude gradients, belonging to the tone alone, might serve as evidence that the tone actually turned off during noise. Thus we might predict that apparent continuity might be reduced as compared to the apparent continuity of a tone which remained at a constant intensity before and after the noise burst.

We can set up an alternative prediction from a simpler neural persistence hypothesis. According to this explanation, the tone sets some neural system into activity. When the masking noise burst comes on, it activates some of the same neural circuitry as did the tone. Therefore the circuit persists in its activity and we hear the tone continue through the noise. This theory would predict that turning down the tone by 10 dB just prior to the noise onset would certainly have no worse an effect upon continuity than lowering the tone by 10 dB overall and making no change immediately before the noise. On the other hand turning up the tone just before the noise might boost the neural activity corresponding to the tone and *increase* the illusion of continuity.

EXPERIMENT I

METHOD

Subjects

Twenty graduate and undergraduate students in psychology at McGill University volunteered as subjects. They were all naive as to the purpose of the experiment.

Procedure

The subjects were tested individually in a small room. They were told that on each trial they would hear an alternation of a tone and a noise burst and that the tonal signal should sound continuous for short noise-burst durations but discontinuous for long noise-burst durations. They were asked to use a knob to adjust the noise-burst duration until the tone changed from sounding continuous to discontinuous, or vice-versa. They were encouraged to use the full range of the knob, and were instructed to turn the knob in both directions until they had centered on the point between perceived continuity and discontinuity of the tone (which will be referred to as the threshold for continuity). The subjects were then to push a button which would stop the trial and record the noise duration. They would then turn the knob back to the shortest noise-burst duration, causing the computer to start the next trial. Thus, each trial began with the noise burst at its shortest duration. There was a 500 msec, 2000 Hz warning tone at the beginning of each trial. Each subject was given a practice trial consisting of the 76 dB tone with 0 msec amplitude ramps (no ramps); all subjects demonstrated an ability to hear continuity of the tonal signal in this practice trial. It took most subjects approximately 30–45 minutes to complete the 32 trials.

Stimuli and Conditions

On each trial the listener was presented with a repeating cycle of a 500 msec, 1000 Hz sine tone signal alternating with a 91 dB noise burst of adjustable duration (see Fig. 1). The tone consisted of a steady-state portion with amplitude

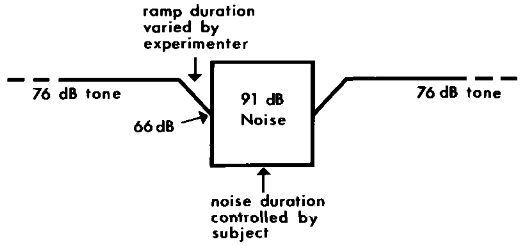

FIGURE 1 Experiment I: stimulus with falling amplitude ramp preceding the noise burst: one cycle of the recycling pattern.

changes (linear ramps) before and after the noise bursts. The amplitude of the steady-state portion was either 76 dB or 66 dB. The linear amplitude ramps of the tone adjacent to the noise burst were either rising or falling. When the amplitude fell before the noise burst, there was a corresponding rise to the steady-state amplitude just after the noise burst, as shown in Figure 1. Likewise when the amplitude rose before the noise burst it fell to its steady state value just after the burst. Pre-burst and post-burst ramps in the tone were always of the same duration. It should be noted that conditions are always labelled according to what happened just *before* the burst; what happens afterward is essentially the 'mirror image.' In some conditions (0 msec ramp) there was no amplitude change before or after the noise burst. The tone simply turned off at the beginning of the noise burst and on again at the offset of the noise.

There were four basic conditions in the experiment. Two of them were steady tones of 66 or 76 dB with no amplitude ramps (0 msec ramps). The other two were (1) a tone of 66 dB steady-state briefly rising to 76 dB and (2) a 76 dB steady-state tone briefly falling to 66 dB at the margin of the noise burst. These 'rising' and 'falling' conditions were further distinguished according to the duration of the ramp (10, 25, or 50 msec). This variation in duration was introduced because we had no notion of what the optimal duration would be. There were, therefore, a total of eight different conditions presented to subjects in four randomized blocks for a total of 32 trials.

Apparatus

The 1000 Hz tonal stimuli were generated by a PDP-11 computer operating a Wavetek model 136 VCA/VCG tone generator by means of a D/A converter. The noise signals were generated by a Lafayette model 15011 white noise generator and filtered through a Multi-Metrics AF-520A active filter to produce band-passed noise of 500 to 1500 Hz. The noise and tone sources were switched in and out by the computer at the proper locations in the sequence. The noise bursts had rise and fall times of less than 1 msec. At the noise burst onset, the tone was attenuated from its ending level to less than 10 dB in less than 1 msec, remained at this level throughout the 91 dB noise, and then rose to its post-burst starting level in less than 1 msec as the noise switched off. Onsets and offsets of the tone occurred at the first positive zero crossing of the sine wave from the free-running oscillator. Thus there was an average error of 0.5 msec (±0.5 msec) which varied randomly across conditions. The abrupt start and end of the sine wave did not generate any transient that was audible to the experimenters.

All dB measurements were made using a General Radio type 1551-C sound level meter set at B weighting and coupled to the headphones by a flat-plate coupler. The signal sources were mixed and then amplified using a Sony TA-1055 stereo amplifier, and the sequence was presented to the subjects through Sennheiser HD-414 stereo headphones in a separate room, which was a normal indoor room with no special acoustic isolation.

The subject could control the duration of the noise signal using a knob connected to the computer through an A/D converter. He ended each trial by pressing a button which also caused the computer to store the most recent adjusted noise duration.

RESULTS AND DISCUSSION

The mean thresholds between perceived continuity and discontinuity of the tonal signal are shown in Figure 2. For noise durations shorter than the threshold value, the tone was heard as continuous. Hence high values signify better continuity. The results show that for the 76 dB condition, in which the amplitude decreased before the noise burst, continuity became poorer as the duration of the amplitude ramp increased. When the amplitude increased before the noise (the 66 dB steady-state tones), there was a slight, but inconsistent, decrease in continuity as the amplitude ramp duration increased. An analysis of variance showed that there was a significant difference between the threshold adjustments for the two steady-state tone dB levels, $F(1,19) = 9.88$, $p < .01$, and a significant effect of amplitude ramp duration, $F(3,57) = 6.73$, $p < .005$. There was no significant interaction between these two main effects.

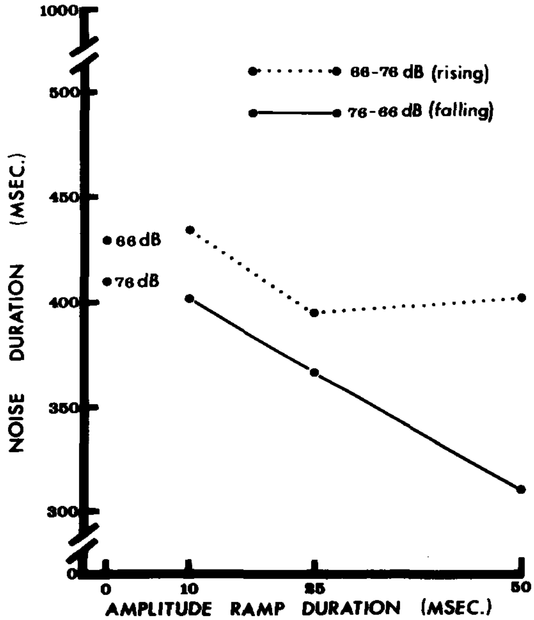

FIGURE 2 Experiment 1: mean thresholds between perceived continuity and discontinuity. For noise durations shorter than the threshold value, the tone was heard as continuous. Hence high values signify better continuity.

The most important result is that decreasing the amplitude by 10 dB before the noise burst and increasing it again after the noise burst (the 76 dB condition) caused a decrease in perceived continuity. In this case, a slight dropping edge has been imposed on the tone just prior to the noise. Even so, the tone is still at 66 dB just as the noise turns on. If this final pre-interruption level were the only factor affecting perceived continuity, the continuity should have been exactly as good as with the 66 dB no-ramp condition (0 msec ramp), since the final amplitude is the same in both cases. One can see in Figure 2 that this is not true; the falling ramps produce continuity which is lower than the 66 dB non-ramped condition. Thus, the edge, which suggested that there might be a termination of the tonal signal during the noise burst, was more important in affecting the continuity threshold than was the energy of the noise relative to the tone.

The results are not predictable from a simple neural persistence hypothesis. The downward ramping conditions should be no worse than the unramped 66 dB condition according to this simple model.

The results for the 66 dB steady-state tones showed that making the tone louder before the noise burst does not, however, produce the reverse effect as might be predicted from the neural persistence hypothesis. That is, such a procedure apparently does not make the tone perceptually continue more than with no amplitude ramps. In fact, there was a slight tendency for a decrease in continuity as the duration of the amplitude ramp increased in this condition. The explanation for this may lie in the fact that the auditory system responds to *any* change in the tonal signal, either up or down, as indicating a discontinuity in the tone. This might reduce the perception of continuity.

The effects of duration suggest that the noise sometimes masks the loudness changes in the tone. As the point of transition between the steady state and ramped portions of the tone are moved further away from the borders of the noise, and thus escape its masking effects, these loudness changes in the tone exert a stronger effect on the perceived continuity. This interpretation is consistent with the idea that the continuity effect with steady-state tones arises from the masking by the noise of the sudden drop in loudness of the tone at the onset of the noise. Lacking this 'discontinuity' information, the auditory system projects the sound into the noise.

EXPERIMENT II

Experiment II was designed to allow us to look more systematically at the effect of introducing discontinuities in the tonal signal. Specifically, the following questions were investigated: (1) What is the effect of increasing the duration of the amplitude change beyond 50 msec? (2) Is there any difference between changing the amplitude by 10 dB or 20 dB? (3) Is there any difference between changing the amplitude up or down? We also eliminated the shorter ramp durations (since these seemed to have smaller effects) and added one longer ramp duration to see if ramps longer than 50 msec would have any effect.

TABLE I
Stimulus conditions used in Experiment II

	Amplitude just before noise		
Steady-state amplitude	0 ramp	Up	Down
80	80	—	70;60
70	70	80	60
60	60	70;80	—

METHOD

Subjects

Thirty subjects participated in this experiment. Thirteen subjects were paid young adults recruited from the McGill University campus between school sessions, and 17 were graduate and undergraduate students in psychology who volunteered their services. In addition, there was one other subject whose continuity thresholds were all above 1 second (the maximum possible in the experiment) and who was therefore eliminated.

Stimuli and Procedure

As in Experiment I, the tonal stimuli were 500 msec, 1000 Hz sine tones alternating with 90 dB band-passed (500–1500 Hz) noise bursts. In this experiment, the durations of the amplitude changes of the tone were 0 msec (instantaneous on and off), 50 msec, or 100 msec, thus extending these values beyond the 50 msec maximum in Experiment I.

Nine different stimulus conditions were created by varying the factors of ramp duration, direction of change and amount of change in the ramped position of the sine tone. The rise and fall times of the noise burst were always under 1 msec. The nine basic stimulus conditions are outlined in Table I. There were three steady-state amplitudes, 80, 70 and 60 dB. The 80 dB signal either remained constant (0 ramp) or was ramped downwards to 70 or 60 dB. The 70 dB signal remained constant or was ramped upwards to 80 dB or downwards to 60 dB. The 60 dB signal either remained constant or was ramped upwards to 70 or 80 dB. As in Experiment I, these changes in amplitude before the noise were accompanied by corresponding changes back to the original level after the noise. (Descriptions of amplitude changes, such as 60–70 dB, will always refer to the change before the noise burst.) The 0 msec amplitude change conditions (simple steady-state tones) were presented twice as many times as the other conditions, so that one-third of the trials had no amplitude changes, while two-thirds had amplitude changes. The trials were presented randomly in three blocks, for a total of 54 trials. There was also one practice trial consisting of a 70 dB tone with no amplitude changes. All of the subjects heard continuity of the tone in this practice trial.

All other procedures were the same as in Experiment I, except that, because of the softer nature of some of the tones (60 dB) in Experiment II, subjects were tested in an Industrial Acoustics Audiometric testing room model 1202. Background noise in the room plus noise from the various electronic devices (amplifier, mixer, etc.) was 47 dB as measured through the headphones using a flat-plate coupler. Most of the background noise was of very low (inaudible) frequencies apparently caused by the building air conditioning system.

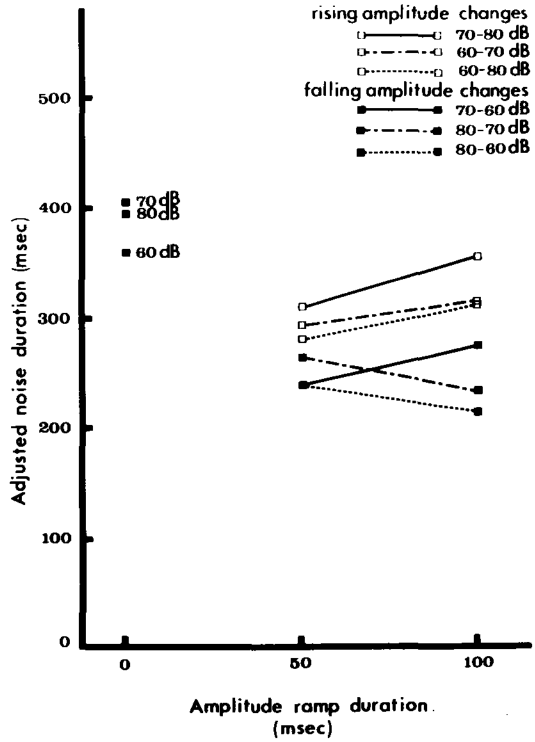

FIGURE 3 Experiment II: mean thresholds between perceived continuity and discontinuity. For noise durations shorter than the threshold value, the tone was heard as continuous. Hence high values signify better continuity.

RESULTS AND DISCUSSION

The results of the experiment are presented in Figure 3. As can be seen from the figure, any change in the amplitude of the tonal signal produced a decrease in the continuity threshold over the steady-state levels, a result similar to that of Experiment I. An overall comparison, using the Sheffé method, of stimuli with no change in amplitude, with stimuli having falling amplitude changes, revealed a highly significant difference, $F(1,29) = 53.01$, $p < .001$. In addition, there was a significant difference between steady-state stimuli and stimuli having rising amplitude changes, $F(1,29) = 14.24$, $p < .025$. To look in greater detail at the effects of direction of amplitude change, nine analyses of variance were performed. Only the conditions in which there were amplitude changes were included in these analyses. Three separate analyses were done to look at the effect of having a common starting point in amplitude, three comparing conditions with common mid-points (the amplitude at the middle of the change), and finally three analyses comparing conditions having common end points. The results of these analyses are summarized in Table II.

One of the main problems which this experiment was designed to investigate was whether there was any difference between continuity thresholds for tones that decreased in amplitude before the noise burst as compared with tones that increased in amplitude before the noise. Five different comparisons are directed towards this question. Three of these are the comparisons between conditions having common

TABLE II
Summary of the results of separate analyses of variance conducted on the results of Experiment II

	Variables		
Comparisons	Transition[a]	Duration	T × D
Same mid point[b]			
80–70; 70–80	***(U > D)		*
80–60; 60–80	***(U > D)		
70–60; 60–70	**(U > D)	*	
Same start point			
80–70; 80–60			
70–80; 70–60	***(U > D)	**	
60–70; 60–80			
Same end point			
70–80; 60–80		**	
60–70; 80–70	**(U > D)		
70–60; 80–60			**

[a] This variable refers to different things in different analyses. When the comparison is between changes in different directions (e.g., 70–80; 70–60), it is the effect of direction of change. However, when both changes are in the same direction (e.g., 80–70; 80–60), it is the amount of change (10 or 20 dB).
[b] The numbers refer to dB changes before the noise burst.
*$p < .05$.
**$p < .01$.
***$P < .001$.
U > D indicates that the upward ramp led to greater continuity of the tone.

mid-points. One is a comparison between conditions with a common starting point (70–80; 70–60), and one with a common end point (80–70; 60–70). In every case, there is a highly significant effect of the direction of amplitude change; whether the comparison is between conditions having common starting points, mid-points, or end points seems to make little difference. In all comparisons between upward and downward transitions with a common mid-point (e.g., 60–80 vs 80–60 dB), the downward transition always leads to lower continuity.

Among the comparisons involving a common starting amplitude, only the 70–80 versus 70–60 dB comparison was significant. Again, the direction of change proves to be the most important factor.

Finally, when conditions sharing a final ending amplitude are compared, only the 60–70 vs 80–70 (i.e., the ones differing in direction of change) show a difference, with the downward ramp again leading to less continuity.

The occasional effects of amplitude change duration, and the interaction of the two main effects, are due to the rise in continuity observed in some conditions at 100 msec. Obviously, at the extreme (very slow amplitude changes) we would expect the continuity thresholds to come back to the steady-state levels, since such very slow amplitude changes would perceptually be very similar to steady-state tones.

A final point, in relation to amplitude change, is that there seems to be no significant effect of the amount of amplitude change (10 dB or 20 dB). Table II shows that the transition variable was never significant for any of these comparisons.

One fact evident in comparing Figures 2 and 3 is that the steady-state conditions do not line up in the same order (e.g., from soft to loud) in the two experiments. However, in each experiment the order of the steady-state conditions taken alone was not statistically significant. The change from one experiment to the other was probably due to sampling error.

GENERAL DISCUSSION

The results of the present experiments and those in the literature can give us some insight as to the mechanism responsible for the auditory continuity effect. We would like to suggest that the auditory system, at a pre-attentive level, decomposes the acoustic input and generates a description of the imput as a composite of co-occurring but distinct signals. One product of this decomposition is auditory stream segregation (Bregman & Campbell, 1971; Bregman & Dannenbring, 1973; Bregman & Rudnicky, 1975). This is a case where an acoustic input is described perceptually as a cooccurrence of two sources, neither of which masks the other. The illusion of continuity is a special case of decomposition where one signal is perceived as masking or *occluding* the other (when it really does not). This perceptual 'description' will arise when certain evidence is present. There are two types of evidence. One is evidence available immediately from the acoustic properties of the situation. The second type depends on prior learning, as in phonemic restorations. However, it is unlikely that prior learning can generate a perception of 'occlusion' when the acoustic evidence says that it is impossible. If you cut a phoneme out of the sentence and do not fill the gap with loud noise, there will be no phonemic restoration (Warren, 1970).

The acoustic evidence, therefore, is primary in affecting the decomposition. It is probably processed in the following way. Whenever there is a sharp discontinuity either in the frequency spectrum or in overall loudness, the possibility exists that a second source, B, has replaced a first one, A, as the dominant shaper of the acoustic spectrum. The acoustic system must now determine what has happened to A. Two alternatives exist: A has either turned off or continued on. Acoustic evidence for continuation is the following: (1) B is much louder than A and might mask A if A were present; (2) the activity of the neural circuitry that registered A has not stopped altogether after B's onset; (3) A reappears immediately at the 'off' edge of B; (4) there are no perceptible (i.e., not masked) silences (sharp drops in amplitude) between A and B; (5) there is no perceptible amplitude gradient in A, just prior to the onset of B, to suggest that A might be changing during the interruption.

With regard to the fifth principle, we were surprised to find in the current experiment that even an increasing amplitude gradient acted against the perceived continuity of the tone to some degree. While decreasing gradients are more effective, any sort of amplitude change seems to inhibit the interpolation process.

The perceptual *content* of the interpolation (restoration) depends on what is predictable from the analysis of signal A prior to and after its interruption. If certain speech sounds are predictable, they are inserted. If a continuation of a glide in pitch, or a change in direction of the glide is predictable, that is what will be inserted (Dannenbring, 1974). And finally, if a simple steady-state pitch is predictable, the insertion will be a steady-state pitch.

RÉSUMÉ

Deux expériences sur l'illusion de continuité d'un son présenté en alternance avec des éclats de bruit intense. Les expériences montrent que de brèves modification dans l'amplitude des sons, quand elles se produisent avant et après un bruit, réduisent l'illusion de continuité; cette réduction est plus marquée quand l'amplitude décroît plutôt que de croître avant le bruit. Ces résultats suggèrent que l'illusion de continuité implique un défaut d'information sur les contours sonores.

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(*First received 1 March 1977*)
(*Date accepted 27 June 1977*)