The effect of blanking on the identification of temporal order in three-tone sequences

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Trained subjects were asked to identify the temporal order of three 20-msec tones (891, 1,000, and 1,118 Hz), which were immediately followed by a fourth tone. It was found that this added tone, irrelevant to the observer's task, decreased the identifiability of the preceding three-tone pattern, as compared with that of the same pattern in isolation. Such a blanking of the memory of the three-tone sequence was most effective when the frequency of the fourth tone was either identical to that of the first pattern tone or when it lay 1/6-1/3 octave above the highest pattern frequency. The blanking effect was strongest when the duration of the fourth tone was equal to that of the pattern components.

Perception of successive nonspeech sounds, presented either as a continuously recycled pattern or as a single sequence, has been the target of a number of recent studies (Divenyi & Hirsh, 1974; Leshowitz & Hanzi, 1972; Neisser & Hirst, 1974; Warren, Obusek, Farmer, & Warren, 1969; Watson & Wroton, 1972). One conclusion, common to these diverse studies, is that accuracy of perception of longer sequences, whether inferred from the observer's ability to discriminate the frequency of one of the components in the sequence or to recognize the temporal order of components, is less accurate than frequency discrimination of isolated sounds (Shower & Biddulph, 1931) or ordered perception of pairs of sounds (Hirsh, 1959; Ronken, 1972). Such a decrease in perceptual accuracy seems to stem from an interference by components late in the sequence with the processing of earlier components. These early parts of the sequence are likely to be still at some sensory, rather than memorial, stage of the perceptual process (e.g., in the "echoic memory"; Neisser, 1967), so that any interference in this fragile process could result in a loss of information.

Backward-interference phenomena of this type have been extensively studied in the visual modality (Averbach & Coriel, 1961; Sperling, 1960). What have been called "erasure," "blanking," or "Type B masking" (Kolars, 1962) effects have appeared to constitute the basis for inferences concerning the nature of visual short-term memory. Although these studies dealt with sequential (temporal) interference in the perception of spatially organized visual displays, one may consider as not entirely inappropriate the analogy between these phenomena and interference effects found in the perception of sequentially presented auditory stimuli (Julesz &

Hirsh, 1972). Indeed, there is evidence suggesting that some postsensory backward interference in the perception of auditory sequences may also be an important factor, as indicated by studies in frequency discrimination (Watson & Wroton, 1972) or in temporal-order identification (Neisser & Hirst, 1974). It is likely that isolation of such an effect could contribute to understanding of perception of nonspeech sounds, and of speech perception as well. The present study was undertaken as one step in a more systematic investigation of these backward, blanking effects.

The specific problem of the present paper arose directly from a previous study (Divenyi & Hirsh, 1974), in which identifiability of the temporal order in three-tone sequences was examined in some detail. One of the chief conclusions of that work was that the last tone of the triplet was perceived as the most salient stimulus feature by all observers in nearly all experimental conditions. Now, it may be that discriminability of the temporal order of the first two tones in the sequence can be considered as depressed by the presence of the last tone. Although it was found that identification of some orders of the three tonal components, i.e., those two orders in which the frequency change was unidirectional ("low-middle-high" and "high-middle-low"), was much more accurate than identification of the order of two tones (Hirsh, 1959), the data also indicated that pairwise discriminability of the three-tone sequences was always poor between any two sequences in which the terminal frequency was common. The two sequences which were most often mistaken for one another by all subjects were the two with the same final frequency and with bi-directional frequency change ("low-high-middle" and "high-low-middle"). Thus, it appears that perception of the temporal order of two tones became more difficult by the addition of an immediately following third tone, unless it continued a direction of frequency change established by the first two. The present study attempts to investigate to

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what extent identification of the temporal order of a set of three tones would be modified by the addition of a temporally contiguous fourth tone.

METHODS

The sounds of the experiments consisted of four contiguous sinusoids presented in a single sequence. These tones were obtained from three instantaneous changes in the frequency of a tone burst, at 20-msec intervals. The tone burst was abruptly turned on and off and had a constant amplitude. At its onset, the tone burst was always started at a positive-going zero crossing. The first three tones of the sequence, called the *pattern*, consisted of the same three frequencies: 891, 1,000, and 1,118 Hz, covering a total span of 1/3 octave. In each trial, however, the order of presentation of these three frequencies was random. That is, the fourth tone could follow any one of the six possible patterns that represented the six permutations of three tones. The frequency and the duration of the fourth tone was constant within each block of 100 trials. The stimulus was presented monaurally through one of a pair of earphones (TDH 49 in MX 41/AR cushions) at 85 dB SPL to observers listening simultaneously. Stimulus control was accomplished with a PDP-8/S computer interfaced with an Iconix Model 6255 time base, a Wavetek Model 116 triggerable voltage-controlled oscillator, and a Grason-Stadler Model 1287 electronic switch. The same computer also provided trial-by-trial feedback and recorded the subjects' responses.¹

Three male and one female subject with normal hearing and previous musical experience participated in the experiments. Their ages ranged from 16 to 22 years. Their task consisted of identifying the temporal order of the three pattern tones while ignoring the fourth tone, by pressing the appropriate one of six graphically labeled keys on a response box. Visual feedback was given after every response. For each condition, 400-600 responses were collected. The experiment reported below was preceded by 6 weeks of training. During the greatest part of this training period, the subjects learned to identify three-tone sequences that arose from permuting the three pattern frequencies, without the added fourth tone. Training procedures were identical to those described in a previous paper (Divenyi & Hirsh, 1974).

The 6 x 6 stimulus-response confusion matrices obtained for each of the experimental conditions were analyzed to determine identifiability of each pattern-sequence against a background of the five other sequences combined. For each of the six patterns in each condition, this was achieved by contracting the original 6 x 6 matrix into a 2 x 2 matrix, the four cells of which corresponded to the number of hits, false alarms, misses, and correct rejections. The particular pattern was taken as the "signal," while the ensemble of the five other patterns was considered "noise." The percentage of correct decisions calculated from this matrix was translated into d' units. This d' value was called the *identification index* for the particular pattern. Since there were six stimulus patterns, six such identification indices were calculated for each experimental condition. Each index expressed the identifiability of one of the six permutation patterns. The arithmetic mean of the six pattern identification indices was considered to adequately represent the overall identification performance of a subject in a given experimental condition, and is called the *overall identification index*.²

Reasons for adopting this averaged d' measure as an indicator of the overall performance lay primarily in its simplicity and general understandability; also, it is free from response bias to the same extent as is the single-interval detectability index, d'_{YN} . On the other hand, such a measure tends to make the difference between performance levels obtained in different conditions appear less pronounced than an information measure would do (e.g., percentage of information transmitted), due to nonindependence of the six individual identification indices that constitute the average. Thus, the overall identification index is a *conservative* indicator of the effect of a given experimental condition on performance.

The overall identification index of the six patterns presented

Figure 1. Diagram of the stimulus sequence: rectified envelope of the stimulus tone burst. Broken lines represent instantaneous frequency changes, with the four frequencies labeled as f_1 , f_2 , f_3 , and f_4 . At each trial, f_1 , f_2 , and f_3 were determined by random permutation of the three frequencies 891, 1,000, and 1,118 Hz. The frequency of the fourth tone, f_4 , was varied from condition to condition, within the range of 494 to 2,000 Hz; its duration, t_4 , was set at 20 msec for Experiment 1, whereas it was manipulated in 20-msec steps from 0 to 100 msec in Experiment 2.

without an added fourth tone corresponded to a d' value of 3.2 on the average, for the same four observers.

RESULTS

The Effect of the Frequency of an Added Tone

How does the frequency of a fourth tone, appended to a three-tone pattern, influence the identifiability of the pattern? This question was the subject of Experiment 1. The frequency of the fourth tone, f_4 , could take one of nine values within the range of 494 to 2,000 Hz, that is, a range extending roughly one octave below and one octave above the middle pattern frequency. This frequency was varied only from condition to condition; it was held constant within each block of 100 trials. The duration of the fourth tone, t_4 , was set at 20 msec throughout the experiment; that is, all four tones of the stimulus sequence were equal in duration. Figure 1 shows the pattern of the stimulus. Four subjects participated in the experiment.

In Figure 2 (top), overall identification indices of all six patterns are displayed as a function of the frequency of the fourth tone, both for the four subjects' individual data and for their average. The data corresponding to the rightmost point on the abscissa show, as a reference, the performance of the same subjects when they had to identify the six patterns in the absence of any added tone. The bars on each datum point in Figure 2 represent ± 1 standard error of the mean to indicate expected variability, where the standard error of the mean is calculated from the total variability across trials and across subjects.

It is apparent that an added tone, regardless of its frequency, interfered with the identification of the order of the three pattern tones. The magnitude of

Figure 2. Experiment 1. (Top) Overall identification index of the three-tone patterns (averaged identification indices of all six patterns for each condition) as a function of f_4 , the frequency of the tone immediately following the pattern. (Bottom) Identification index of a selected three-tone pattern (low-high-middle) as a function of f_4 . Numbers refer to the individual performances of four subjects, whereas the line represents their average results. The bars on the datum points represent two units of standard error of the mean.

this interference, however, varied as a function of the fourth tone's frequency. The general trend of the curves in Figure 2 (top) suggests that identification of the patterns suffered least when the frequency of the added tone was remote with respect to the pattern frequencies (494 or 2,000 Hz). On the other hand, identification indices of all four subjects was most depressed when the frequency of this irrelevant fourth tone lay 1/6 to 1/3 octave higher than the highest pattern frequency (1,266 or 1,413 Hz). These two observations were valid, with only minor exceptions, for all subjects. Nevertheless, there were some differences in the respective performance levels of the four subjects. Subject 1 being clearly superior to the other three observers.

Although overall identification indices are good indicators of the average identifiability of the six patterns, they could mislead by hiding possible

changes in the identifiability of *individual* patterns, that could occur as a function of changes in the frequency of the added tone. An example of how the identification of a given pattern was affected by changes in the frequency of f_4 is illustrated in Figure 2 (bottom). Here, the ordinate refers to the identifiability of the pattern "low-high-middle" (891 Hz-1,118 Hz-1 kHz). The frequency effect in this figure is very similar to the one seen in Figure 2 (top) with the exception that, beside the performance minimum which occurred when f_4 lay 1/6-1/3 octave above the pattern range, there is yet another condition in which identifiability of the pattern was markedly depressed by the added tone, one in which frequency f_4 was identical to that of the first pattern frequency, that is, 891 Hz. Two performance minima like those seen in Figure 2 (bottom) for the pattern "low-high-middle" (one minimum at f_4 being either 1,265 or 1,413 Hz and one at f_4 being equal to f_1 , the frequency of the first pattern tone) were also observed for the other five patterns, the identification data of which are not shown here. Since each of the three pattern frequencies could be the starting frequency in two patterns, the minimum associated with the first pattern frequency does not appear in the averaged data shown in Figure 2 (top). Table 1, however, illustrates the averaged identification performance for those patterns in which the frequency of any of the three components coincided with that of the added tone. The d' values in this table indicate that the performance of each subject shown in the $f_4 = f_1$ column is lower than this performance seen in the two other columns ($f_4 = f_2$ and $f_4 = f_3$). This minimum is significant for two subjects and for the four subjects averaged.

The Effect of the Duration of an Added Tone

In Experiment 1, the three pattern tones as well as the interfering fourth tone had the same 20-msec duration. Whether an added tone having a duration different from that of the pattern components would influence the identification of temporal order in the preceding three-tone sequence was tested in Experiment 2. The stimulus was almost identical to that used in the previous experiment. However, the duration of the fourth tone, t_4 , was variable with its frequency, f_4 , held constant either at 705 Hz or at 1,413 Hz, that is, either a third octave below the lowest pattern frequency or a third octave above the highest pattern frequency. The range of t_4 durations investigated in this experiment extended from 0 to 100 msec, in 20-msec steps. Within each block of 100 trials, both the frequency and the duration of the added tone were fixed. Three trained subjects served as listeners. As in the previous experiment, they were instructed to identify the temporal order of the three pattern tones and to ignore the fourth tone.

Results of this experiment are illustrated in Figure 3a for the $f_4 = 1,413$ -Hz case, and in Figure 3b for the $f_4 = 705$ -Hz case. Both figures

Table 1
Averaged Identification Indices in Experiment 1 (d') Showing Identifiability of Those Patterns in Which f_1 , f_2 , or f_3 Coincided With f_4 (Conditions With $f_4 = 891$ Hz, 1 kHz, and 1,118 Hz)

Subject	$f_4 = f_1$		$f_4 = f_2$		$f_4 = f_3$	
	Mean	Confidence Interval*	Mean	Confidence Interval*	Mean	Confidence Interval*
1	1.59	1.84 1.22	2.54	2.78 2.27	2.97	3.28 2.74
2	.69	.97 .42	.77	.99 .53	1.05	1.30 .87
3	.76	1.03 .57	.93	1.21 .77	1.19	1.36 .92
4	1.39	1.64 1.16	1.88	2.13 1.65	1.85	2.09 1.64
All Subjects	1.10	1.23 1.00	1.45	1.58 1.36	1.60	1.74 1.49

*Confidence interval: $\begin{cases} \text{Mean} + \text{standard error of the mean} \\ \text{Mean} - \text{standard error of the mean} \end{cases}$

display the overall (average) identifiability of the six patterns as a function of the duration of the fourth tone. Again, variability indicated in the figures corresponds to ± 1 standard error of the mean.

The data for both fourth-tone frequencies suggest that the added tone decreased the identifiability of a preceding three-tone pattern, no matter what its duration was, but the effect of the fourth tone was strongest when its duration corresponded to the duration of each pattern component (20 msec). The exception is the curve that represents data of Subject 3 in Figure 3b ($f_4 = 705$ Hz), whose identification performance decreased monotonically with increasing duration of t_4 .

"Good Continuation"

In the results of Experiment 1, there is one exception to the general trend which shows that an added fourth tone decreases identifiability of the temporal order in the preceding three-tone sequence. When the fourth tone represents a continuation of a *unidirectional* frequency change begun by a certain three-tone pattern, identifiability of that pattern was found to be less depressed. Two cases fall into this category: the pattern low-middle-high (891 Hz-1 kHz-1,118 Hz) followed by a 1,266-Hz tone and the pattern high-middle-low (1,118 Hz-1 kHz-891 Hz) followed by a 791-Hz tone, both cases representing three consecutive 1/6-octave frequency changes either upwards or downwards. Table 2a indicates that the two cases yield the highest relative identification performance (identification index for the given pattern minus overall identification index) across all possible frequencies of the added tone. Table 2b makes the same point by comparing identification performances for the six patterns when f_4 was either 791 or 1,266 Hz.

This finding suggests that melodies consisting of all-up or all-down frequency jumps of identical size are easier to recognize than are others in which the direction and/or the size of the frequency jumps are

Figure 3. Experiment 2. Overall identification index of the three-tone patterns as a function of t_4 , the duration of the tone immediately following the pattern. Numbers represent individual performances of three subjects, and the line their average. The bars on the datum points represent two units of standard error of the mean. (a) $f_4 = 1,413$ Hz; (b) $f_4 = 705$ Hz.

Table 2a
Relative Identifiability of the Two Patterns With Unidirectional Frequency Change (Identification Index of the Pattern Minus Overall Identification Index) Across All Frequencies f_4 and for All Subjects Combined

	f ₄ (Hz)								
Pattern	494	705	791*	891	1000	1118	1266†	1413	2000
LMH	.17	.48	.40	.04	.23	.98	1.35	1.01	.59
HML	.14	.45	.88	.45	.12	-.27	-.05	-.18	.29

* F_4 1/6 octave below the lowest pattern frequency.

† F_4 1/6 octave above the highest pattern frequency.

Table 2b
Relative Identifiability of the Six Individual Patterns (Identification Index of the Pattern Minus Overall Identification Index) for the Two Frequencies f_4 , Lying 1/6 Octave Below (791 Hz) and 1/6 Octave Above (1266 Hz) the Pattern Frequency Range, Averaged Across All Subjects

f_4 (Hz)	Pattern					
	LMH*	MLH	LHM	HLM	HML*	MHL
791	.40	-.06	-.06	-.18	.88	-.96
1266	1.35	-.63	-.22	-.36	-.05	-.08

*Pattern with unidirectional frequency change.

irregular. Thus, it appears that addition of a fourth tone may enhance the perceptual salience of a preceding three-tone sequence when all four tones follow a unidirectional frequency change. As noted above, a third tone, too, was seen to enhance identifiability of the temporal order of two preceding tones when the three tones comprise a regular ascending or descending melodic pattern (Divenyi & Hirsh, 1974).

DISCUSSION

The results of these two experiments show that identifiability of the temporal order in three-tone patterns is, most often, considerably diminished by the addition of a fourth tone which immediately follows the pattern, even when the observers are instructed that this added tone is irrelevant to their task.

Localizing the origin of these effects was not the aim of the present study. However, one should consider that the backward interference observed in Experiments 1 and 2 occurred at an intensity level and in temporal and frequency regions where neither the audibility of the individual components was appreciably impaired (Samoilova, 1960), nor did the pitch of contiguous tones ever fuse into a single pitch percept (Nabelek, Nabelek, & Hirsh, 1973). Thus, while it cannot be excluded that the suppression of temporal-order identifiability may have been correlated with a certain decrement in the clarity of the sensory image of the stimulus, one must conclude that the contribution of such a "smearing" of the sensory image was not the principal factor in the observed decrement of performance. This is why we propose to use a label for this phenomenon that will

distinguish it from masking—which is commonly accepted to refer to interference affecting mainly operations of the sensory system. To designate the type of interference seen in the present experiments, we have adopted the term "blanking," borrowed from the vision literature where some authors have repeatedly argued that short-term memory for displays is highly sensitive to "trace erasure" or "blanking" caused by a subsequently presented stimulus (Kollers, 1962; Sperling, 1960). Blanking-type (rather than masking-type) interference is not an uncommon phenomenon in audition, either. Its effects on speech perception have been extensively used as a tool to study perceptual-cognitive processes (Broadbent, 1958, pp. 11-18; Neisser, 1967, pp. 223-242). Blanking has also been observed in nonspeech stimuli, where it has been seen to interfere with discrimination of the frequency of a tone embedded in a longer sequence (Watson & Wroton, 1972), memory for one or several tones (Deutsch, 1973; Elliott, 1971), as well as temporal-order identification in four-component (hiss-scratch-high tone-low tone) sequences (Neisser & Hirst, 1974).

In accord with what is known of the nature of interference in visual short-term memory, results of the present study indicate that blanking was least effective when the added tone was clearly unlike the pattern tones (*either* in frequency or in duration). Here the four-tone stimulus complex could be perceived as two separate entities (Gestalts), three tones plus one. On the other hand, it was most effective when the added tone was similar enough to the pattern tones (*both* in frequency and in duration) so that it could fit into the pattern and form a whole pattern different from that of the three-tone sequence to be identified. In the special case, however, where the pattern and the added tone together form a single pattern that consists of regularly ascending or descending frequencies, the blanking effect of the fourth tone becomes much attenuated.

If blanking is to be distinguished from masking, it is useful to describe some of its characteristics. Auditory blanking appears to exhibit certain similarities to masking, as well as certain differences. To some extent, the fourth tone has a role analogous to that of a masker in a backward masking situation, with the difference that, instead of affecting the detectability of the preceding tones, the added tone

interferes with either the memory trace or the perceptual processing of the preceding sequence, or both. The point on which the two phenomena look most similar is that both are strongest when the frequency or frequency range of the probe (in the present case, the pattern) coincide with that of the interfering stimulus (i.e., the added tone). In Experiment 1, it was seen that identifiability of a given pattern was markedly depressed when the frequency of the blanking tone coincided with the first pattern frequency, thereby creating two partially overlapping patterns which were likely to compete for the subject's response. (For instance, with the lowest pattern frequency, i.e., 891 Hz, as the frequency of the added tone, the whole four-tone sequence could have been perceived either as the pattern "low-high-middle" followed by "low" or as the pattern "high-middle-low" preceded by "low.") Furthermore, blanking, like masking, may be caused by a tone whose frequency lies outside the frequency range of the pattern, or signal. It is well known that in simultaneous as well as in backward masking of a tone by another tone, the effective frequency band of the masker extends farther above the probe frequency than below it (Gol'dburt, 1964, pp. 58-68; Wegel & Lane, 1924).³ In blanking, however, tones having their frequency $1/6$ - $1/3$ octave above the frequency range of the pattern interfere much more strongly with the identification of the pattern below than do those tones whose frequency falls below the pattern range. This conclusion agrees with findings of other psychophysical experiments. Watson and Wroton (1972), for example, noted that discriminability of the frequency of a given component in a 10-tone sequence is poorer when its frequency lies in the lower part of the sequence's composite spectrum than when it lies in the upper part. Observers were also found to be more successful in identifying the last tone of a three-tone sequence when its frequency was the highest in the set of three pattern frequencies than when it was either of the two other frequencies (Divenyi & Hirsh, 1974). Thus, contrary to the general rule in tone-by-tone masking, higher tones appear to have a greater blanking effect on lower tones than vice versa. Another difference between masking and blanking follows from the effect of the interfering tone's duration. While, within certain limits, backward masking has been found to be a monotonic function of masker duration (e.g., Gol'dburt, 1964, pp. 79-81), blanking seems to be strongest when the duration of the interfering stimulus is identical to that of the components in the pattern which it succeeds.

Thus, the present data suggest that addition of a fourth tone does, indeed, decrease identifiability of the temporal order in the preceding three-tone sequence, just as addition of a third tone was found to decrease identifiability of the order of two preceding tones (Divenyi & Hirsh, 1974). Similarly, one may

suppose that blanking of a similar kind may fully or partially explain why identification of the order of components presented in a continuously repeating sequence is poorer than identification of the order of components in the same sequence presented only once (Leshowitz & Hanzi, 1972; Warren et al., 1969).⁴

CONCLUSIONS

When a pattern consisting of three 20-msec tones is followed by a fourth tone, the perceptual image of the pattern will be most often blanked. The extent of such a blanking may be considerable, *unless* the interfering tone is sufficiently different from the pattern components to make the whole four-tone complex segregate into two separate Gestalts: the pattern and the blanking tone. Properties of auditory blanking, as inferred from the present study, suggest that blanking probably affects memory processes more than sensory processes.

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NOTES

1. The experiments were conducted in the Signal Detection Laboratory of the Central Institute for the Deaf.
2. When examining the acoustic waveform of the stimulus, a certain ringing (approximately 6 msec in duration and at least 20 dB down from the last cycle of the electrically driven signal) was observed. This ringing was similar to the one reported in an earlier paper (Divenyi & Hirsh, 1974), and its frequency seemed

to follow that of the preceding tone. Since in the present experiments this tone was the fourth in the sequence which did not change, no matter what the order of the first three frequencies was, the ringing which followed the last tone could provide no cue for the identification of the temporal order of the first three tones.

3. This conclusion, however, does not meet the unanimous consent of other workers, as far as backward masking is concerned. More recent, unpublished studies indicate that, in certain conditions, backward-masked thresholds may be either symmetrical on each side of the probe frequency or a reverse asymmetry could be found with respect to the frequency asymmetry exhibited by simultaneous masked thresholds.

4. Although results of Neisser and Hirst (1974) point toward an opposite conclusion, this discrepancy may be at least partly attributed to differences between their experimental procedures and those of either Warren et al. (1969) or Leshowitz and Hanzi (1972).

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