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Pure-tone masking patterns in nonsimultaneous masking conditions

KEN'ICHI MIYAZAKI

Department of Psychology, School of General Education, Niigata University, Igarashi, Niigata 950-21

TAKAYUKI SASAKI[1]

Department of Psychology, Faculty of Arts and Letters, Tohoku University, Kawauchi, Sendai 980

Forward and backward masking patterns were obtained using a 70-dB SPL sinusoidal masker whose frequency was varied and a 3 000-Hz sinusoidal probe signal through an adaptive two-interval forced choice (2IFC) procedure. The temporal course of the residual excitation pattern produced in the auditory system by the masker could be represented by a set of forward masking patterns at different temporal locations after the end of the masker. The shape of the forward masking patterns was dependent upon the probe delay time and the phenomenon of the maximum masking frequency (MMF) shift was observed at relatively long delay time. Although results of forward masking are free from undesirable interaction effects between a masker and a probe, several other distorting effects are inevitable. As potential causes of these effects, the nonlinear growth of the excitation, the quality-difference cue for detection of a probe, and the off-frequency listening strategy are discussed. As for backward masking, an amount of masking was relatively small for the whole frequency range examined, and so any distinct patterns were not observed.

Key words: auditory system, forward masking, backward masking, frequency selectivity, temporal property.

The frequency selectivity of the human auditory system can be evaluated psychophysically by the masking experiment where the stimulus frequency is varied as an independent variable. Classical studies on this issue usually used a simultaneous masking paradigm where a listener detects a relatively long probe signal in the presence of a continuous masking stimulus (e.g., Egan & Hake, 1950; Small, 1959; Wegel & Lane, 1924; Zwicker & Feldtkeller, 1967). The masking pattern obtained in this way could be considered to reflect the physiological excitation pattern elicited in the auditory system by the masker. In this sense it has been called the psychophysical excitation pattern (Zwicker, 1975). However it cannot be free from the interaction effects between a masker and a probe. Of these effects the amplitude fluctuation perceived as beats or roughness, the combination tones, and the two-tone suppression can exert marked influences on the shape of the masking pattern (see, Greenwood, 1971; Moore & Glasberg, 1981, 1982). In consequence one cannot evaluate accurately the frequency response characteristics of the auditory system from the result of simultaneous masking.

An alternative approach is forward masking where a brief probe is presented after the offset of a masker, so the undesirable interaction effects mentioned above can be avoided. This paradigm has been often used in recent studies because it is expected to provide more accurate measures of the frequency selectivity of the auditory system (e.g., Moore, 1978; Vogten, 1978). Moreover one can measure masking patterns by presenting a brief probe at different temporal locations before, during, and after a masker, resulting

[1] Now at Miyagi Women's College, Sakuragaoka, Sendai 980.

in a set of the masking patterns along a temporal dimension. In other words by combining a time axis with a frequency axis orthogonally, the masking pattern at a single temporal location could be extended to the so-called spatio-temporal masking pattern which could reflect the dynamic property of the frequency response caused by the masker. Fastl (1979) explored along this line and summarized his results using a three-dimensional representation which he called the transient masking pattern. More recently, Miyasaka (1983) has performed similar experiments using a pure-tone masker with an abrupt onset and offset and displayed an atlas of temporal masking effects. It should be noted however that backward, simultaneous, and forward masking have different mechanisms and that several factors which are mentioned above and will be considered later would influence the performance differently for each of three masking paradigms. It is therefore open to question to combine the backward, simultaneous, and forward masking patterns uniformly in a three-dimensional representation, although such a representation is indeed appealing. It may be needed to specify the contribution of the external factors to each masking result.

In the previous paper (Miyazaki & Sasaki, 1981) we measured the pure-tone masking patterns using a brief probe tone at different temporal positions before, during, and after a tonal masker, resulting in the backward, simultaneous, and forward masking patterns, respectively. It was observed that the simultaneous masking pattern contained a marked notch due to the combination tone and had considerably shallower slopes possibly due to the two-tone suppression. On the other hand the forward masking results showed no such effects. It was also observed that the global shape of the forward masking pattern was dependent upon the delay time of the probe tone after the offset of the masker. And on some delay conditions the frequency of the probe at which the maximum masking occurs does not correspond to the masker frequency, but is slightly higher than it. The masking pattern in a backward condition had rather irregular shape. As the origin of backward masking is considered to be completely different from that of forward masking, results of backward masking should be interpreted differently from those of forward masking.

It must be noted that there remained a methodological problem in our previous experiment where the method-of-adjustment was used as a psychophysical procedure. This procedure is considered to be susceptible to variation of a subject's decision criterion in a detection task possibly producing much variability in the performance. Furthermore, if the criterion changes somewhat systematically with experimental variables, results obtained should contain the systematic deviation.

In the present study where some of our previous experiments are repeated, we employ an adaptive two-interval forced choice (2IFC) procedure which could offer measures corresponding to certain performance levels in a detection task more efficiently (Levitt, 1971). It seems that this procedure is more appropriate as the psychophysical procedure for the masking experiment than the method-of-adjustment. With this procedure, forward and backward masking patterns are obtained at several temporal locations after the masker's offset or before its onset. The primary aim of the present study is to obtain further information about the temporal course of the post-stimulatory excitation in the auditory system from the forward masking data. Additionally two issues we are specifically concerned about are whether the phenomenon of the maximum masking frequency (MMF) shift as found in our previous study is reproduced here and whether distinct masking patterns are observed in a backward masking condition. To check the linearity of masking, the level dependence of the masking pattern is also examined in a forward masking condition in a supplementary experiment.

Method

Stimuli. In contrast to the classical masking paradigm where probe thresholds are measured at various frequencies with a masker which is fixed in frequency and in level, in the present study thresholds of a probe fixed in frequency were measured in the presence of a masker whose level was fixed but whose frequency was varied as an independent variable. The probe was a 3 000-Hz sinusoid of 10 ms in duration between half power points. The masker was a 70-dB SPL sinusoid whose frequency was varied from 1 000 to 3 500 Hz and whose duration was 250 ms. The onset and offset of all stimuli were shaped with linear ramps of 5 ms.

In a forward masking condition where the probe follows the masker, intervals between half power points of the masker's offset and the probe's onset were 5, 15, 25, 35, and 65 ms, i.e., silent intervals between the masker and the probe were 0, 10, 20, 30, and 60 ms, respectively. In a backward masking condition, the probe preceded the masker with silent intervals of 0, 10, and 20 ms. In a supplementary experiment where the level dependence of the masking pattern is examined, probe thresholds were measured in a forward masking condition of 0-ms silent interval with masker levels set at 20, 35, 50, 65, and 80 dB SPL. Any other details were identical to the main experiment.

Procedure. Thresholds were determined using a two-interval forced-choice (2IFC) procedure with a transformed up-down paradigm (Levitt, 1971). A trial began with the button pressing by an observer and after a 1-s interval two observation intervals followed. The masker was contained in both intervals but the probe was randomly presented in either interval. The observer had to specify in which interval the probe had occurred by pressing one of two response buttons. A visual feedback was given immediately after the response. The probe level was attenuated by 2 dB after two consecutive correct responses, and increased by 2 dB after each incorrect response. A trial sequence contained twenty-four reversals, i.e., changes in the direction of attenuation. The first two reversals were discarded and an average of the remaining reversals was taken as the threshold corresponding to the level of 71% correct response on the psychometric function. The initial level of the probe in each trial sequence was set at an appropriate value where it was easily detected. Three threshold determinations were repeated for each masker frequency on separate days and an average of them was taken as the probe threshold.

Apparatus. Stimuli were generated by a function generator (Kikusui, 458A) and a sine-wave generator (Kikusui, 417A) whose onset/offset ramps were determined by two electronic switches (Rion SB-10A). Timing of the stimulus sequence was controlled by a programmable timer (Izumi PRG-S) and a digital pulse generator (Rion TG-04A). Stimulus intensity was controlled by an attenuator (Kikusui 984A) and an amplifier (Technics SU-9400). The stimuli were presented monaurally to a listener seated in a soundproof room through an electrostatic headphone (Koss ESP-9B) whose output characteristics was measured by the manufacturer using a modified 6-cm^3 coupler with a Brüel & Kjaer Type 4134 microphone and Type 2619 preamplifier.

Subject. Two listeners (KM and TS) took part in the experiment as subjects. They were well experienced in psychoacoustic experiments and had normal hearing.

Results

Probe threshold patterns in a forward masking condition are displayed in Fig. 1 as a function of the masker frequency for each listener separately. The parameter is signal delay time. An arrow at the ordinate represents the threshold level of the probe obtained in the absence of the masker through an equivalent procedure, indicating 8.1 dB SPL for TS and 9.2 dB SPL for KM. Each masking pattern shows marked asymmetry due to the well-known asymmetry of the excitation pattern of the auditory system. Slopes of the pattern could be regarded as reflecting a filter characteristics of the auditory system. Our results indicate that in a condition of no silent interval between a masker and a probe the slope of the lower side is about 34 dB/oct for Subject KM and 44 dB/oct for Subject TS and the slope of the higher side at the steepest part is about 300 dB/oct and 390 dB/oct, respectively.

Figure 1 also shows the temporal course of the masking pattern after the masker's cessation. It is evident that the shape of the pattern becomes shallower on both sides as the probe delay increases for both listeners. When the probe delay is relatively short, the frequency the maximum masking occurs is equal to the probe frequency. However it can be seen that at least for Subject KM the maximum masking frequency (MMF) tends to shift to the lower frequency as the probe delay increases. The MMF shift effect was more pronounced in our previous experiment, but in the present one it is less clear because in the present case the peak of the masking pattern is rather rounded in long-

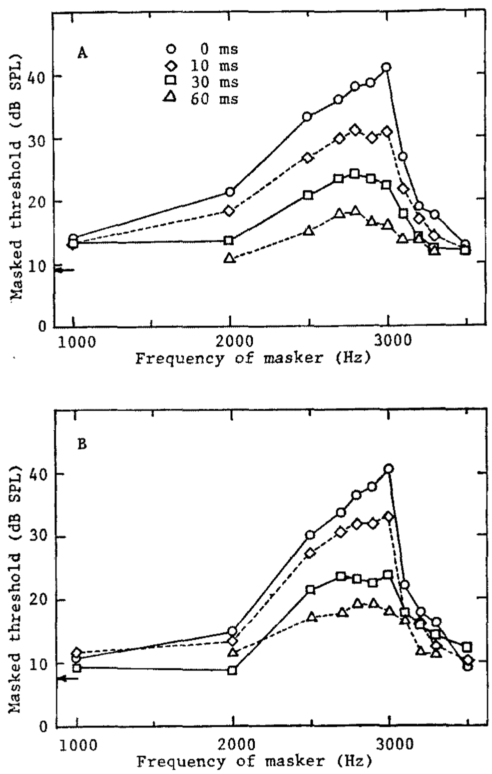

Fig. 1. Forward masking patterns as a function of masker frequency obtained from KM (A) and TS (B). Parameters are silent intervals between masker offset and probe onset. An arrow represents a threshold without masker.

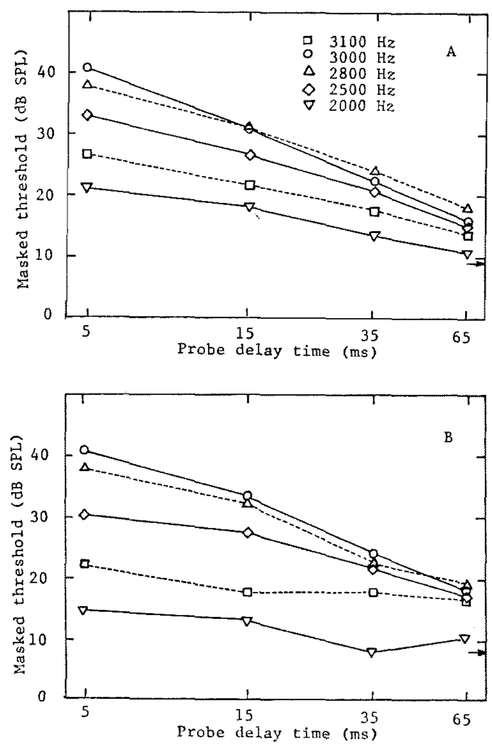

Fig. 2. Masked thresholds as a function of signal delay time replotted from Fig. 1 (A for KM and B for TS). Parameters are masker frequencies. An arrow represents a threshold without masker.

er delay conditions.

In Fig. 2 masked thresholds in a forward masking condition are replotted as a function of the probe delay time for different masker frequencies, displaying the decay process of the masking effect more directly. It could be seen that they are approximately linear functions on a plot of dB vs. logarithms of the probe delay time, except for the masker frequencies where an amount of masking is relatively small. A line could be fitted to data points for each masker frequency by the least squares method. The time the masked threshold reaches to the absolute threshold level could be calculated by extrapolation. The mean decaying times calculated in this manner for masker frequencies of 2 800, 2 900, and 3 000 Hz are 286 ms for TS and 177 ms for KM.

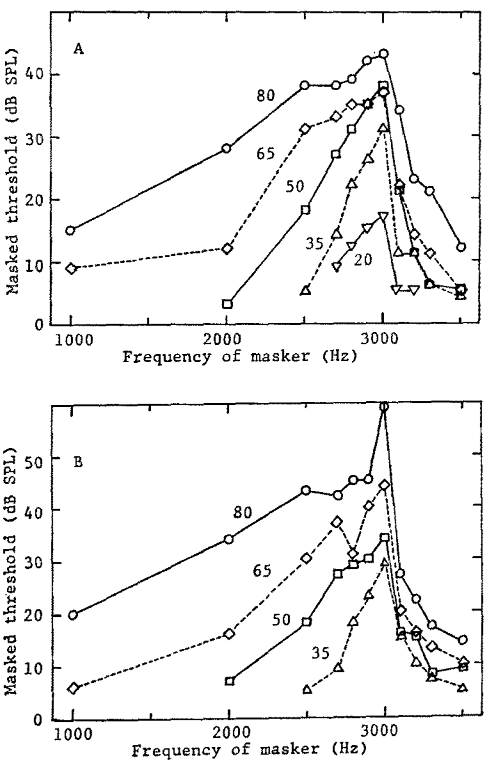

Fig. 3. Forward masking patterns as a function of masker frequency from KM (A) and TS (B). Parameters are masker levels in dB SPL.

The forward masking patterns at various masker levels are shown in Fig. 3. Some nonlinearity can be seen; generally the lower slope becomes flatter but the higher slope becomes sharper as the masker level increases.

Results in a backward masking condition are shown in Fig. 4. An amount of masking is much less and any unequivocal frequency patterns are not observed.

Discussion

The probe threshold patterns obtained here are regarded as indicating the activity within a fixed probe frequency channel caused by a fixed-level masker as a function of the masker frequency. So they may be called the fixed-input filter patterns (Verschuure, 1981), which show the output level of a filter to which inputs of a constant level and of different frequencies are delivered. On the other hand the

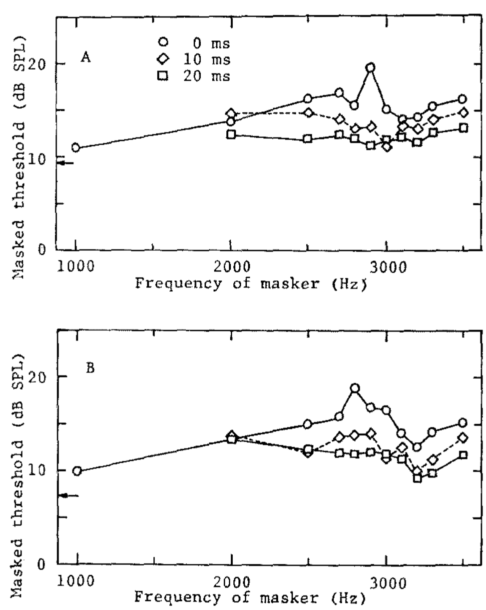

Fig. 4. Backward masking patterns as a function of masker frequency from KM (A) and TS (B). Parameters are silent intervals between probe offset and masker onset. An arrow represents a threshold without masker.

classical masking patterns as obtained in our previous study are regarded as displaying the activity of a fixed-frequency masker in probe channels of different frequencies as a function of the probe frequency, so they could provide the measures of the excitation pattern produced by the masker fixed both in frequency and level. The masking pattern of this type may be called the fixed-input extension pattern (Verschuure, 1981). Theoretically the input-filter pattern and the input-extension pattern should be equivalent to each other except that they are symmetrical about a vertical axis. Comparing the present results and our previous ones, such equivalence is less exact. The failure to obtain the accurate correspondence may be mainly due to the difference of the psychophysical procedure and of the experimental paradigm. It could be stated that the maskng pattern obtained here provides more reliable measure of the excitation pattern because the variabilities due to the change of the subject's decision criterion and the local irregularities of the absolute threshold are absent here.

Another type of masking data is the psychophysical tuning curve (PTC) that is obtained in an experiment where the probe is fixed in its level and its frequency and the masker level necessary to just mask the probe is plotted as a function of the masker frequency. This pattern is considered to be plotted the input level necessary to produce an output of a constant level from the probe channel for various input frequencies, and therefore could be called the fixed-output filter pattern. The output-filter pattern and the input-filter pattern like a present one should be symmetrical about a horizontal axis so far as the system behaves linearly.

The slopes of the patterns obtained here were about 40 dB/oct for the lower side and about 300–400 dB/oct for the higher side. These values are roughly comparable to those of the PTCs (Kidd & Feth, 1981; Moore, 1978; Vogten, 1978) and the neurophysiological tuning curves at a peripheral level (Evans, 1975; Kiang, Watanabe, Thomas, & Clark, 1965). It must be noted however that the tuning curve and the masking pattern of the input-filter type cannot be compared directly because results of our supplementary experiment (Fig. 3) and of many other investigations demonstrated the marked nonlinearity of the response of the auditory system.

The masking patterns are susceptible to several factors which make them less accurate measures of the frequency response of the auditory system. First the results of the supplementary experiment showed that with the increase of the masker level the slope of the lower side of the masking pattern became shallower whereas the slope of the higher side became steeper, suggesting the nonlinear growth of the excitation pattern with the stimulus level. Such nonlinear level-dependence of the excitation pattern, also confirmed by other investigators (e.g., Kidd & Feth, 1981; Verschuure, 1981), could make the steeper side of the masking pattern somewhat curved, resulting in the overestimation of the steepness of that side near the peak. Such an effect could be seen in the forward masking pattern (Fig. 1). Secondly, in a forward masking situation the so-called quality-difference cue as suggested by Moore (1980) can cause a significant effect; when the frequency difference between a masker and a probe is relatively small, they sound similar and therefore it is difficult to differentiate the probe from the masker, resulting in the elevation of the thresholds. On the contrary when the probe frequency is remote from the masker the probe could be easily differentiated from the masker, with the result of lowering the thresholds. As the result, the peak of the masking pattern would be emphasized, and the frequency selectivity would be overestimated. Thirdly, the influence of the off-frequency listening as revealed by Leshowitz and Wightman (1971) must be considered. In forward masking the probe must be short in order to increase the temporal resolving power. As the result, the energy of the probe necessarily spreads in a certain frequency range. In our study the probe duration was set at 10 ms as a compromise between the demands of the temporal acuity and the spectral acuity. As the listener's optimal strategy for detecting the probe is to maximize the probe-to-masker ratio within a listening band, it might be possible on some occasions that the listener would shift the listening band to the off-frequency region where the maximum probe-to-masker ratio could be obtained. The off-frequency listening strategy would give an advantage when the probe is located at a lower frequency region of the excitation pattern of the masker, whereas it would not be so effective when the probe is higher than the masker because in this case the off-frequency probe energy is masked by the upper spreads of masker energy. Consequently the steepness of the lower skirt of the excitation pattern would be overestimated. It should be noted that all three artifactual factors mentioned above may produce an overestimation of the frequency selectivity of the auditory system.

Masked thresholds as a function of the probe delay time (Fig. 3) indicated that the masking effect declines more rapidly when an amount of masking is greater. It is seen that they would reach an absolute threshold level in roughly equal delay times, implying that the induced response would decay out approximately in the same time regardless of its initial level. This observation is corresponding to the decay characteristics of the auditory sensation suggested by Plomp (1964). Similar results were also obtained by several researchers (e.g., Kidd & Feth, 1981; Widin & Viemeister, 1979). It should be noted that in our case some discrepancy exists among the estimated decay times for different conditions of the masker frequency, possibly due to the above mentioned factors influencing the shape of the masking patterns. The temporal course of the masking patterns displayed in Fig. 1 is considered to represent the temporal course of the post-stimulatory excitation pattern; as the probe delay time increased the shape of the masking pattern became shallower. Hence the interval between the masker and the probe should be as short as possible for the purpose of estimating the shape of the ongoing excitation pattern from the residual masking pattern.

In addition to the time-dependent property of the residual excitation pattern mentioned above, one remarkable phenomenon is that in some conditions the maximum masking occurs not when the masker frequency is equal to the probe but when the probe is slightly higher than the masker. This phenomenon called the MMF shift has been often observed by several investigators both in simultaneous and nonsimultaneous masking situations (Moore, 1981; Munson & Gardner, 1950; Vogten, 1978). One way to explain this phenomenon is to hypothesize that the location of the maximum response on the basilar membrane is level-dependent. As the probe level is always lower than the

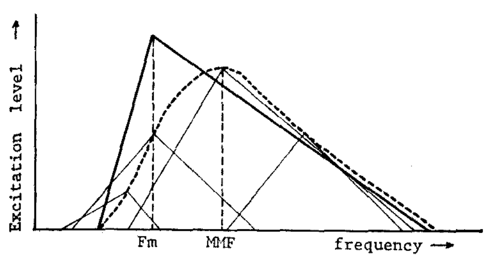

Fig. 5. A schematic illustration for explanation of the MMF shift on the basis of the internal excitation patterns. A triangle drawn by thick solid lines represents the excitation pattern produced by a masker. Triangles of thin solid lines represent the excitation patterns of probe signals. A thick dashed curve illustrates the masked threshold pattern. Note that in this representation frequency of the masker is fixed and frequency of the probe is varied for convenience of illustration. Fm: Masker frequency, MMF: Maximum masking frequency.

masker, locations of the maximum of their response patterns are not coincident even if their frequencies are equal. Some physiological studies on the displacement of the basilar membrane and cochlear microphonics have supported such a hypothesis (von Békésy, 1960; Honrubia & Ward, 1968; Rhode, 1971). Recently Moore (1981) has obtained the correlation of the MMF shift and the post-stimulatory pitch shift and explained the MMF shift on the basis of the effect of the quality-difference cues. However he offered no explanations to the pitch shift effect. As for our results the MMF shift could be explained by the combination of the level-dependent asymmetry of the excitation pattern and the off-frequency listening. As schematically illustrated in Fig. 5, the probe could be detected when its excitation exceeds that of the masker by a certain amount. As the probe level is musch lower than the masker in a condition of relatively long probe delay, the lower slope of the probe excitation pattern is shallower than that of the masker excitation pattern. When the frequency of the probe is equal to or lower than the masker, it should be optimal for detection to set the listening band to the off-frequency region on the lower side of the probe excitation pattern. This strategy is less effective when the probe frequency is higher than the masker by more than a certain amount. Then the listener would shift the off-frequency listening strategy to the on-frequency listening strategy, in which the listening band would be located around the peak of the probe excitation. Consequently the maximum masking occurs when the probe frequency is higher than the masker by a certain amount. When the probe delay is relatively small, the degree of asymmetry of the excitation pattern is not so different between the masker and the probe because the difference of their levels is not so large and therefore the off-frequency listening strategy is not so effective. Hence the MMF shift is not observed in a condition of short delay time.

Results of backward masking were quite different from those of forward masking; an amount of masking was relatively small over the whole frequency range examined and any explicit frequency patterns were not observable. With a 2IFC procedure in an adaptive paradigm, the performance of probe detection has not much disturbed by a followed masker. While it is known that forward masking is related to the residual excitation of the masker or the post-stimulatory adaptation at the level of the primary fiber response, the origin of backward masking is rather equivocal. It might be suggested that backward masking is of somewhat central origin, which is quite different to forward masking. Hence the frequency response at a peripheral level could not be reflected on the results of the backward masking. It could be mentioned, therefore, that backward masking could not be a useful tool for estimating the frequency selectivity of the peripheral auditory system.

In conclusion we have obtained forward masking patterns at several temporal locations after the end of the masker. The temporal course of the masker-elicited excitation could be estimated from them. However it has been discussed that several artifactual factors, such as the nonlinear growth of the excitation, the quality-difference cues for detection of a probe, and the off-frequency listening strategy could exert considerable influences on the shape of the masking pattern. It may be mentioned that the forward masking pattern has limitations as an accurate representation of the excitation pattern of the auditory system because it cannot avoid effects of these factors. If the effects of these factors could be measured quantitatively, more accurate representation of the frequency response of the auditory system could be derived by subtracting those effects from the forward masking data. Moreover it should be noted that the forward masking pattern is reflecting not the ongoing but residual excitation after the masker's end. The finding that the shape of the forward masking pattern depends upon the probe delay time suggests that the condition of the shortest delay could provide the pattern most similar to the ongoing pattern. However they, even, may not be the same completely. More data concerning to the decaying characteristics of the excitation are needed in order to estimate accurately the ongoing frequency response from the measures of the residual excitation.

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