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Some results on lateral suppression obtained in a partial-masking lateralization paradigm

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Results were reported of psychophysical forward-masking experiments using a lateralization method. A general interpretation of masking was given, considering masking to be the combined result of three different mechanisms: the overlap mechanism, the adaptation mechanism, and the suppression mechanism. The aim of this study was to demonstrate the use of the lateralization method in a masking experiment. Masking was measured in a band-widening experiment using a test tone frequency of 3 kHz, which is the center frequency of the masking noise. It was found that the effect of the suppression mechanism depends in a complex way on the difference between masker level and test tone level, as does the bandwidth at which maximum masking occurs. These level effects could be described qualitatively by means of nonlinear excitation patterns.

INTRODUCTION

This paper presents some tentative results from a study of the masking process. Its primary goal is to describe a new measuring technique which uses a lateralization paradigm in forward masking. The new technique is applied to a band-widening experiment. The following paragraphs describe the theoretical and experimental framework within which the results of the experiment have been obtained.

For the interpretation of masking data we propose the following explicit hypothesis regarding underlying mechanisms. A test tone will be masked by a masker whenever the "central detector" is unable to detect the presence of the test tone in the responses in the "auditory channels." The channels can be identified with primary auditory-nerve fibers. The detector has to detect the test tone response in neutral spike trains on the basis of either rate or synchrony information (e.g., Siebert, 1970, 1972). In case of simultaneous masking the channels are excited by both test tone and masker. Detection performance will then depend on the ratio of the responses to test tone and masker. This consideration leads to the well-known hypothesis that masking is due to the overlap of excitation patterns across the channels. A test tone is masked when the masker's excitation pattern covers the test tone pattern (e.g., Zwicker, 1958). Detection of the test tone requires the signal-to-noise ratio to exceed a certain criterion value. We term this mechanism the overlap mechanism. In absence of the masker; its role in the signal-to-noise ratio is played by internal noise. The internal noise determines the absolute threshold.

Theoretically, the overlap mechanism can be treated as a linear mechanism. There are, however, two additional factors that influence the excitation patterns, viz., lateral suppression and adaptation, of which at least suppression is essentially a nonlinear one. Lateral suppression (e.g., Sachs and Kiang, 1968; Houtgast, 1974) is assumed to work instantaneously, and to precede the adaptation mechanism. [It is reasonable to assume that suppression occurs at the input of the hair cell (cf., Sellick and Russell, 1979), whereas adaptation appears to occur at the hair cell output (cf., Furukawa and Matsuura, 1978)]. The change in sensitivity of the auditory system during stimulation, i.e., adaptation, follows a gradual time course, as does the recovery after termination of the masker. The relatively slow post-stimulatory recovery of sensitivity is displayed in forward masking (de Maré, 1940). The amount of adaptation is apparently related to the excitation level.

Thus, the results of a forward-masking experiment reflect the masker's excitation pattern. We assume that partial masking reflects the same processes as threshold masking, but to a lesser extent.

It is a psychophysical challenge to try to separate the role of the three mechanisms experimentally. The obvious difference between simultaneous and forward masking is that in forward masking there is no direct interaction between the excitation pattern of the test tone and the masker. Thus, in forward masking, detection is determined by the recovery state of the sensitivity and is limited by internal noise. The overlap mechanism is inoperative except for this internal noise floor. Hence, the comparative study of the two gives information about the overlap mechanism. An additional difference, and thereby a factor complicating the above analysis, is that the test tone in a simultaneous-masking situation is subjected to the overlap mechanism, whereas this is not the case in forward masking. It appears difficult to interpret data obtained in a simultaneous-masking paradigm in terms of perstimulatory adaptation and suppression because both test tone and masker are affected. The net effect of adaptation and suppression in the signal-to-masker ratio as seen by the detector is then greatly, if not completely, reduced.

We decided to explore an additional technique where the test tone would be presented to the contralateral ear (henceforth this tone is called the calibration tone). The calibration tone should scan the excitation level of the stimulus or masker in the ipsilateral ear. This is achieved by adding a suprathreshold test tone to the masker. The ipsilateral test tone will be affected by the masker, this effect is measurable in terms of the lateral image produced by test tone and calibration tone. The experimental method is described in detail in Sec. II B. The lateralization method is applicable as a simultaneous as well as a nonsimultaneous technique. It yields a method to determine effects perstimulatory.
If one assumes that the lateral position of test and calibration tone is determined by their relative loudnesses, it is obvious that the results of this experiment are related to partial-masking data.

As an example of the applicability of the lateralization paradigm, we present some data from a band-widening experiment. In this paper we do not explore the time parameter, but we investigate the effect of both masker level and test tone level in a forward-masking situation.

In 1970 Greenwood and Goldberg found, as a result of their physiological experiments, that the firing rate measured in neutrons of the cochlear nucleus first increases with increasing bandwidth of a noise stimulus and then decreases when the noise bandwidth increases beyond a certain value. The noise had a constant spectral density. Ruggero (1973) obtained a corresponding result from primary auditory-nerve fibers.

Comparable psychophysical results have been obtained with nonsimultaneous masking methods. Houtgast (1974) performed the band-widening experiment with the pulsation-threshold method and obtained the same nonmonic result that was obtained physiologically. Schreiner (1977) corroborated Houtgast's results. He observed that the bandwidth at which maximum masking occurs corresponds to the critical band. Houtgast (1974) assumed that the decrease of masking beyond a certain bandwidth is caused by lateral suppression. Leshowitz and Lindstrom (1977), Terry and Moore (1977), and Weber (1978) carried out band-widening experiments with a conventional forward-masking paradigm. Their experiments produced results that are qualitatively similar to results obtained with the pulsation-threshold method. Following Houtgast's interpretation, the difference found between maximum masking and masking measured at the widest noiseband used can be considered a measure of the lateral suppression effect.

We expect a similar trend in lateralization data. The amount of nonmonotonicity may be different, however. In this experiment we explore level parameters. Obviously, a follow-up study investigating temporal parameters is called for.

I. METHOD

A. Experimental setup and procedure

In all our experiments the masker consisted of band-pass-filtered noise with a variable bandwidth centered around 3 kHz. This noiseband was obtained by multiplying band-pass-filtered noise having a variable cutoff frequency by a pure tone having a frequency of 3 kHz. The multiplication was carried out with a 12-bit digital modulator (Willems et al., 1977). After filtering, the slope steepness of the noiseband was about 5 dB/100 Hz. Test tone and calibration tone were pure tones at the center frequency of the noiseband, i.e., 3 kHz.

The duration of the masker was 290 ms, including rise and fall times of 20 ms (see Fig. 1). Test tone and calibration tone had a duration of 20 ms with rise and fall times of 10 ms. All signals had Gaussian-shaped onsets and offsets. Test tone and calibration tone were presented simultaneously 25 ms after the starting point of the masker's offset ramp.

The bandwidth of the noise was the independent variable and could vary from 60 to 2000 Hz. The spectral level of the noise masker and the level of the test tone were independent parameters and could be equal to, respectively, 50, 30, 10 dB/Hz and 75, 65, 55, 35 dB (all dB's re 20 μPa).

The subject was seated in a sound-insulated booth. The stimulus was presented through Pioneer SE-700 headphones. The subject was asked to set, by means of adjustment, the level of the calibration tone that was required to perceive the hearing sensation in the median plane of his head. Between two stimulus presentations there was always a fixed silent interval of 1190 ms. All measuring points were presented three times in a pseudorandom sequence. Three subjects, having normal audiograms and considerable experience in psychophysical experiments, participated in the experiments.

B. Description of the lateralization method

The lateralization method was used as long as 25 years ago for measuring auditory fatigue or adaptation in nonsimultaneous masking conditions (Hood, 1950; Harris and Rawnsley, 1953). More recently, Houtgast (1977), Jesteadt and Javel (1978), and Kearney (1979) have reported on the application of a corresponding lateralization paradigm for measuring suppression in a simultaneous-masking experiment.

The lateralization method is based on the fusion phenomenon that occurs when a pure tone is presented diotically. To one ear of a subject, a masker and a test tone are presented; and simultaneously with the test tone, a calibration tone is presented to the contralateral ear. The calibration tone is equal to the test tone except for its amplitude. The test tone is masked partially by the masker (in this study, in a forward-masking paradigm). In general the test tone remains well perceptible. Thus, the lateralization method is a suprathreshold method. The subject's task is to adjust the level of the calibration tone. This is done in such a way that the subject perceives the hearing sensation which belongs to the combination of test tone and calibration tone, at an arbitrary point of the median plane of his head. We assume that in this condition test tone and calibration tone have equal loudness. Then the adjusted physical level difference be-

FIG. 1. Time course of the stimulus with the lateralization method. R: stimulus to the right ear, L: stimulus to the left ear, M: masker, T: test tone, C: calibration tone.
between test tone and calibration tone is a measure of the amount of (partial) masking caused by the masker.

Besides a level difference between test tone and calibration tone, other factors can also influence the position of the hearing sensation. Examples are a phase difference between the tones, or a difference in time between the presentation of the tones to the ears. When such a difference occurs in our experiments, this may influence the results. These two possible artifacts are discussed below.

In spite of sufficient control of the physical signals used, an internal phase difference might occur between test tone and calibration tone due to interaction between test tone and masker. Therefore, it is important to know what the influence of such a difference between the tones is. The effect of a phase difference on the position of the hearing sensation depends on frequency. This dependence has been tested experimentally. In accordance with results of other investigators (e.g., Licklider and Webster, 1949; Zwischen and Feldman, 1956), we found that such a phase difference is significant only at frequencies below 1500 Hz. We performed our experiments in a frequency region above 1500 Hz, so the possible occurrence of a phase difference cannot have a significant influence on our results.

When a time difference is present between the onsets of both tones, the hearing sensation will be found at the side of the ear first stimulated. This effect is related closely to the precedence effect (Wallach et al., 1949). From an explorative experiment, it followed that with our signals a time difference smaller than 2 ms has very little influence on the position of the hearing sensation. With time differences greater than 2 ms the two contralateral tones no longer fuse perfectly, and it is clear to the listener that a time difference is present. From this it follows that interaural time differences, which are easily controlled to values smaller than 1 ms, will be negligible.

Since the amount of forward masking of the test tone depends on masker level, the decreases in calibration tone level required to center the hearing sensation at different masker levels could conceivably be perceived as different time delays. This is a problem for all experiments measuring time-dependent phenomena, but it should have only a minor effect in the present experiment. It can be minimized by choosing a test tone that is as short as possible, without being too broad spectrally (e.g., a Gaussian-shaped 5–10-ms signal).

To compare the variability of the lateralization method as described above with the variability of the conventional threshold method, an exploratory forward-masking experiment was performed with both methods. A noiseband with a bandwidth from 2 to 4 kHz and a spectral level equal to 30 dB/Hz was used as a masker. The test tone frequency was at the center frequency of the noise masker, i.e., 3 kHz. With the lateralization method, ten different calibration tone levels were pseudorandomly presented ten times each (with a fixed test tone level of 75 dB). The subject was asked to indicate if he perceived the fused hearing sensation at the left- or at the right-hand side of the median plane of his head. With the threshold method, ten different test tone levels were pseudorandomly presented ten times each. The subject was now asked to indicate if he could perceive the test tone. From these results a psychometric function was determined for both methods. For the given conditions both functions coincide almost completely, and a standard deviation of 1.5 dB was found graphically for both methods. It might be expected that with the lateralization method, the level of the test tone has some influence on the slope of the psychometric function. However, we suppose that this will be the case for very low levels (near threshold) only. For all other levels, the decision "left or right" seems to be rather independent of level.

C. Some perceptual impressions

The position of the hearing sensation, produced by a pure tone which is presented diotically through headphones, is somewhere at the median plane of the listener's head. We found that the precise position was dependent on the frequency of the tone. When a low frequency is applied, the hearing sensation is perceived at the back of the head (near the nape of the neck). With increasing frequency the hearing sensation shifts upwards over the back of the crane to the front. The upward shift has also been found with experiments on sound localization. With these experiments, stimuli are presented through loudspeakers. In 1930, Pratt observed that "high tones are phenomenologically higher in space than low tones." His observations were confirmed by Roffler and Butler (1968).

Further, it was noticed that at a relatively high frequency (3 kHz), the hearing sensation seems to exist in a sharpened focus. At lower frequencies the dimensions of this point seem to grow, so that a less precise spot is perceived.

After some training, subjects preferred experiments in which the lateralization method was applied to similar experiments that used the classical threshold paradigm. Threshold methods require in general more concentration and time.

II. RESULTS

In a first experiment the influence of masker level on the masking effect was studied, starting with a fixed test tone level (65 dB). Results are shown in Fig. 2. Because there is no indication that the standard deviation varies systematically with the bandwidth of the noise, we computed an estimation of the mean standard deviation for each curve. Twice this standard deviation is indicated at the left-hand side of each curve.

The curves for the lowest noise level (10 dB/Hz) show that masking increases with increasing bandwidth. Maximum masking occurs at the largest bandwidth (2000 Hz) and amounts to 9–14 dB, depending on the subject. As the noise level increases to 30 dB/Hz, more masking is found for all bandwidths. In addition, we observe that the curves tend to flatten out and for subject AB there is even a decrease. The curves measured at the highest noise level (50 dB/Hz) follow a somewhat different
FIG. 2. Masking curves measured as a function of the bandwidth of the masking noise for three subjects. Three noise levels $N_0$, fixed test tone level $L_T$.

course. The rising character with increasing bandwidth is only initially present in the results of subject AB, at bandwidths larger than 400 Hz the curve bends downwards. Results of HZ show an almost continuous falling character, and JV's results seem to be fairly independent of bandwidth. Results obtained at this noise level (except for JV) are in agreement with expectations based on lateral suppression: masking effectiveness of the central part of a noiseband is reduced by the outer parts, if the bandwidth is large enough. In the figures, this results in a decrease of masking at larger bandwidths.

At the lowest noise level, suppression has no observable influence. To determine whether there is no suppression at all at such a low level (10 dB/Hz) or whether its influence is not measurable with a relatively loud test tone (65 dB), we repeated the foregoing experiment, but now with a fixed difference between masker level and test tone level. This difference was chosen in such a way that at every masker level the test tone remained clearly perceptible. The results of this experiment are shown in Fig. 3. We observe at once that with the subjects AB and HZ, in all three conditions, masking first increases with increasing bandwidth and then decreases. At all three levels, lateral suppression has an observable effect. Further we note that least masking is found at the highest noise level. JV's data differ markedly from the data of the other. To a certain extent this was already the case in the previous experiment, and we will observe similar discrepancies in the next experiments.

The set of data collected up to now can easily be extended by performing two series of measurements, one at a masker level of 30 dB/Hz in combination with a test tone level of 75 dB, and another at a masker level of 50 dB/Hz in combination with a test tone level of 55 dB. Results obtained from these measurements have been combined with results from Figs. 2 and 3, yielding two sets of curves measured at fixed noise levels (30 and 50 dB/Hz) with test tone level as parameter. These two sets of curves are shown in Figs. 4 and 5. For all three subjects, it holds that at a noise level of 30 dB/Hz (Fig. 4), maximum masking is measured at the lowest test tone level (55 dB). However, at larger bandwidths the curves approach each other; this is mainly due to the fact that masking measured at the lowest test tone level decreases relatively strongly (except for JV). It is of particular interest to note that the three curves in each panel do not parallel each other. This can also be observed in Fig. 5, which shows results obtained at a noise level of 50 dB/Hz. The curves obtained at this level also tend to coincide at larger bandwidths. Results of JV are somewhat different again; the differing order of the curves is especially noteworthy.

III. DISCUSSION

The lateralization paradigm produces data with a reproducibility similar to that of a threshold paradigm. The stimulus provides an additional parameter, viz., the level of the test tone. This is inherent to partial-
masking paradigms. After discussion of the data of this particular experiment, we will return to the potential possibilities of the lateralization method.

Our results shown in Fig. 2 indicate that the effect of the suppression mechanism, as apparent from the non-monotonic behavior, increases with increasing masker level. This agrees with results of Houtgast (1974), Terry and Moore (1977), and Weber (1978). Results from experiments on two-tone suppression point to a corresponding level effect (Duifhuis, 1980). Furthermore, our results tend to show that if a maximum occurs in the masking curves, it shifts towards greater bandwidths with decreasing noise level. This would become more prominent if we speculate that at the lowest noise level (10 dB/Hz), a maximum will be present at some bandwidth greater than 2000 Hz. (Unfortunately, for practical reasons it was impossible to carry out measurements at bandwidths larger than 2000 Hz.) Although less clear, Houtgast (1974), using the pulsation-threshold method, also observed such a shift of the maximum. In the results of forward-masking experiments by Weber (1978), no maximum shift is observable. In both studies, masker levels ranging from about 20–50 dB/Hz were used.

Comparing Figs. 2 and 3, we note that the difference between masker level and test tone level is of importance for the observation of lateral suppression. At a masker level of 10 dB/Hz no suppression effect is observed in Fig. 2, but in Fig. 3 it is clearly present. However, because suppression is assumed to be an instantaneous effect (cf., Introduction), it is not possible that the presentation of the subsequent test tone influences the preceding suppression. Consequently, we are led to the conclusion that the sensitivity for measuring suppression depends on test tone level (and test tone versus masker level difference).

The influence of test tone level on the observation of the suppression effect is demonstrated more clearly by the results shown in Figs. 4 and 5. It is not a very surprising effect if one recalls that in general partial masking decreases as the signal-to-noise ratio increases (Zwicker, 1958; Scharf, 1964). Thus it would be a consistent result if the measured interaural level difference would be found to decrease with increasing test tone level. This does appear to be the case for small bandwidths only, however. The behavior at the largest bandwidths shows not much effect of level. This nonuniform behavior may be interpreted on the basis of excitation patterns which are level dependent.

It can be concluded from our previous results (Bezemer, 1978) that the suppression mechanism has its maximum effect at the central frequency region of the masking noise. From this it follows that a test tone with an excitation pattern that occurs just within this frequency region will show the effect of the suppression mechanism most clearly. In general, with increasing signal level, the excitation pattern of a signal becomes progressively broader (e.g., Zwicker and Feldtkeller, 1967). In our case, with increasing test tone level, the excitation pattern of the test tone will extend over a much wider frequency range than just the central part of the masking noise. Therefore, the total average
sensitivity to suppression (within the preceding masker) will then become smaller. This trend describes the results shown in the upper and middle panels of Figs. 4 and 5: the largest difference between maximum masking and masking measured at the widest noise band (2000 Hz) is found at the lowest test tone level (55 dB). In line with this result, the maximum in the masking curve shifts towards a higher bandwidth when the level of the test tone increases.

However, there is a complication in the above interpretation because there are two opposing effects. With increasing bandwidth, and to a certain extent also with increasing level, there is not only an increase in suppression but also a broadening of the excitation pattern of the noise band. The broadening can cause more masking; this depends on the difference between test tone level and masker level. It is not easy to predict whether the suppression or broadening effect will dominate. A quantitative description of these effects would be required. At this point such a description is not available, so for the moment our reasoning is supported by the results showed in this study only. From this it follows that implications about suppression based on threshold measurements cannot directly be extended to above-threshold levels.

Returning to the results shown in Fig. 3 (constant level difference between test tone and masking noise), it may be remarked that least masking is found at the highest noise level. This suggests that compared to the excitation pattern of the masking noise, the test tone pattern becomes relatively broader when both the level of the test tone and the masker are increased. As the high-frequency slope of the excitation pattern is strongly level-dependent (Zwicker and Feldtkeller, 1967), this seems quite plausible, taking into account that the test tone level is higher than the masker level. At this point it is necessary to assume that the high-frequency slope of the noise is determined mainly by its spectral level (and not by its overall level). Also, with these results, only a small suppression effect is observable at the highest test tone level. This agrees with the results shown in Figs. 4 and 5.

The curves measured for subject JV differ in many aspects from the curves measured with the other subjects. Very often his results seem to be nearly independent of bandwidth. Compared with other studies on band widening, this is rather exceptional. The fact that no or only little influence of suppression (decreasing masking with increasing bandwidth) is observable might be less exceptional. Great differences between subjects also have been found in psychophysical studies on two-tone suppression (Shannon, 1976; Duifhuis, 1980). However, it is still possible that influence of the suppression mechanism is present in JV's results. The influence might be derived from the relative positions of the measured curves, e.g., Fig. 2 lower panel. The individual differences found with suppression experiments pose an interesting point for future research.

IV. CONCLUSIONS

The binaural lateralization method has proved itself a convenient and useful tool in partial-masking experiments.

From measured psychometric functions it can be concluded that the sensitivity of the lateralization method is about equal to the sensitivity of the conventional threshold method.

The occurrence of lateral suppression in a band-widening experiment can be measured by making use of the lateralization method. The influence of masker level on the suppression effect has been studied by means of this method at a fixed test tone frequency of 3 kHz.

At a fixed test tone level, the greatest suppression effect is measured at the highest masker level. At a fixed masker level, the greatest suppression effect is measured at the lowest test tone level. With different combinations of masker level and test tone level with a fixed difference between these levels, the size of the suppression effect is not constant. Implications about suppression based on threshold measurements cannot directly be extended to above-threshold levels.

The bandwidth of the noise masker at which maximum masking occurs depends on the difference between masker level and test tone level; as this difference increases, the bandwidth at which maximum masking occurs decreases.

The results are interpreted qualitatively in terms of nonlinear excitation patterns. This interpretation is based on three mechanisms: the overlap mechanism, the suppression mechanism, and the adaptation mechanism. However, the interpretation within the given framework is not completed yet.

The effect of lateral suppression differs considerably between different subjects.

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