ISSN 1063-7710, Acoustical Physics, 2019, Vol. 65, No. 1, pp. 96–102. © Pleiades Publishing, Ltd., 2019.
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ACOUSTICS OF LIVING SYSTEMS.
BIOMEDICAL ACOUSTICS

Frequency Range of Compression for Discrimination of Acoustic Signals with Complex Spectra

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Received September 28, 2017; Revised May 4, 2018; Accepted August 8, 2018

Abstract—Psychophysical experiments on listeners with normal hearing were conducted to discriminate the rippled spectra of an acoustic signal against maskers with different positions of the spectral band relative to the signal band. As the signal level changed from 50 to 80 dB SPL, the on-frequency masker level changed by 29 dB, whereas the low-frequency masker level (the position of the center of the spectral band was from −1.25 to −1 octave relative to the signal) changed by 8.7–9.8 dB. These results are interpreted as 0.3 dB/dB compression of responses to the signal and no compression of the effect of low-frequency maskers. If the spectral bands of the signal and masker partially overlap, discrimination of the spectral structure occurs predominantly in the part of the spectrum that does not overlap the masker spectrum and is subjected to low-frequency masking that is not compressed.

Keywords: hearing, compression, masking, rippled spectra

DOI: 10.1134/S1063771019010056

INTRODUCTION

The compressive nonlinearity of signal processing in the auditory system is a fundamental hearing mechanism. Compression makes it possible to reduce a huge range of sound intensities (up to 120 dB, i.e., by a factor of 10^{12} with respect to the power), making this entire range accessible not only for perception, but also for analysis. Compressive nonlinearity occurs at the level of the cochlea [1] and manifests itself in the responses of auditory nerve fibers [2, 3].

A characteristic feature of cochlear compression (i.e., originating in the cochlea) is that it is maximum in the tonotopic representation of the affecting sound, i.e., in the part of the cochlea for which the sound frequency is characteristic; in neighboring parts of the cochlea, compression is less pronounced or absent [4]. This property of cochlear compression was used to measure it in the human auditory system with a psychophysical method. To reveal the effect of compression, on-frequency masking (i.e. at the signal frequency) and low-frequency masking (at a frequency lower than the signal frequency) have been compared. The on-frequency masker is addressed to the same region of the tonotopic cochlear projection as the signal, so that the masker effect is compressed to the same degree as the signal response. Thus, when the intensity of the signal is changed, the masked threshold is achieved by equally changing the intensity of the masker. As a result, the masker level at the threshold depends linearly on the signal intensity. When the low-frequency masker is applied, the situation is different. The low-frequency masker is less effective than the on-frequency masker, but its effect in the tonotopic representation of the signal is not subjected to compression. Therefore, when the signal level changes, reaching the masked threshold requires a much smaller change in the level of the low-frequency masker. As a result, the low-frequency masker level at the threshold depends nonlinearly on the intensity of the signal. The ratio (in dB/dB) between the changes in the signal level and low-frequency masker level at the threshold reflects the degree of compression of the response to the signal [5–7].

Determination of the compression by masking is difficult, since in addition to the masking, the low-frequency masker also induces some additional effects that can influence compression, including lateral suppression and off-frequency listening [8]. Lateral suppression created by the low-frequency masker reduces the gain of the active mechanism of the cochlea at the locus of the signal representation. Since compressive nonlinearity is a property of the active mechanism, a decrease in its gain results in reduced compression of the response to the signal. The effect of off-frequency listening is that the signal is detected not by the response of the cochlear part that is a tonotopic representation of the signal, but by the response of the part that, despite being less sensitive to the signal, is less subjected to masking. The responses of the locus outside the tonotopic representation are subjected to compression to a lesser extent.

Experiments aimed at measuring compression at its maximum manifestation applied special measures to avoid lateral suppression and off-frequency listening. To avoid the lateral suppression effect, an experimental scheme with forward masking was used rather than simultaneous masking [5]. This technique is based on the fact that lateral suppression is manifested only during the action of the sound and disappears after the sound is turned off. To eliminate off-frequency listening, an additional masker was applied in the expected off-frequency listening region [5] or a signal minimally exceeding the baseline threshold was used, with its detection possible only in the cochlear part most sensitive to the signal [6, 7]. In the latter case, the gap between the masker and signal instead of the signal level was varied for forward masking.

Thus, to maximally reveal the compression of the response to the signal in its (signal) locus of the tonotopic representation required application of signals and maskers with specific characteristics:

—the signal should follow after the masker and not against its background (forward masking) with the time gap between the masker and the signal being large enough so that the lateral suppression that is created by the masker disappeared before the application of the signal, but not too large so that the masking effect did not disappear;

—the signal should be sufficiently weak so that it can be detected only due to the response in its tonotopic representation and not because of off-frequency listening.

These conditions can be met in strictly controlled experiments, but they are not typical for many real sounds. This applies both to target sounds represented by the signal and to other sounds represented by background noise, i.e., maskers. The signals and maskers can completely or partially overlap or be separated with respect to frequency and time. Therefore, the effect of compression on the action of background noise can be different for different signal frequency and time components. Moreover, to understand how signals are detected in the background noise and the role of compression in this, it is important to establish the effect of the masking background not only on detection, but also on discrimination of the signals, since signal recognition and formation of correct responses to them is impossible without their successful discrimination.

The aim of this study is to assess the role of compression in discriminating signals with complex spectra that, according to their characteristics, can be considered a model of complex natural signals. For these model signals, we used sounds with rippled, comb-filtered spectra, i.e., spectra with alternating peaks and troughs within some frequency band. This spectrum can be considered relatively complex, since besides the primary spectral structure determined by such parameters as the central frequency, spectral bandwidth, etc., the rippled spectrum has a finer structure that can be conventionally referred to as secondary, the rippled spectrum pattern. In contrast to many natural signals, the secondary structure of the rippled spectrum can be described by a limited number of parameters (ripple density, their depth and phase), which makes these signals suitable for experimental measurements.

Signals with a rippled spectrum demonstrated their effectiveness for testing the frequency resolution of human hearing ability. The ability of normally hearing listeners to discriminate the rippled pattern of the spectrum was studied in several earlier works [9–12]. The test for discriminating the pattern of rippled spectrum found wide application for controlling the effectiveness of cochlear implants [13–17].

The frequency resolution, which is defined as the ability to discriminate the rippled pattern of the spectrum, decreases both against on-frequency and low-frequency maskers [18–20]. This makes it possible to use signals with rippled spectra in combination with the well-established masking technique for assessing cochlear compression. In this case, it is possible to reveal the role of compression in discriminating the signal spectral patterns rather than in detecting them, which coincides with the aim of this study.

It is impossible to study the effect of compression in discriminating signals for all possible combinations of the signal and masker parameters in one study. The specific aim of this study was to find how the role of compression in discriminating rippled-spectrum signals depends on the frequency relation of the signal and masker. Depending on the relation of the frequency bands of the signal and masker, they can be either completely different with respect to frequency or partially or completely overlap. In this case, different components of the signal and masker can interact between each other according to the rules of either on- or off-frequency masking or according to some intermediate rules. The contribution of compression to the total effect of the masker depends on the interaction between the components of the signal and masker. Some variants of this interaction are considered in this study.

MATERIALS AND METHODS

Subjects

This study involved seven listeners, three men and four women aged from 20 to 45 years. All the listeners had standard audiograms that demonstrated auditory thresholds not exceeding 15 dB in the frequency range in which measurements were performed, from 0.5 to 4 kHz. All the listeners gave informed consent for participation in experiments with audition of sounds below 100 dB SPL.

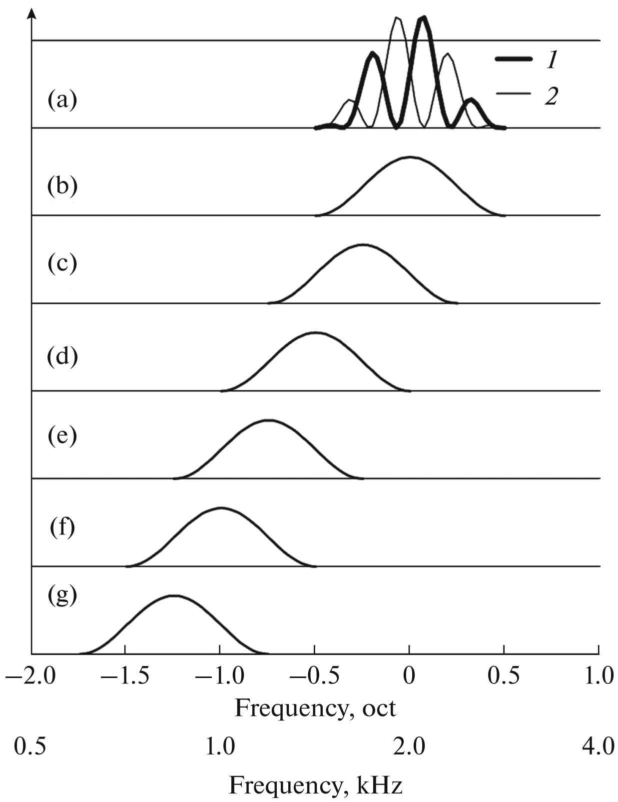

Fig. 1. Spectra of signal and maskers. (a) Signal spectrum, *1* and *2* are spectra that replace each other during reversion of ripple phase; (b)–(g) masker spectra that are shifted from 0 to −1.25 oct relative to signal spectrum. Frequency scale is given in octaves with respect to central frequency (upper scale) and in Hz (lower scale).

Signals

A signal had a rippled spectrum. The spectral envelope was a one-octave-wide cycle of a cosine function of the log frequency centered at 2 kHz (Fig. 1a). The width of the spectral band at a level of 0.5 of the maximum was 0.5 octave (oct). The smooth (cosine) shape of the envelope was used to avoid the effects of sharp spectral edges [21]. Within the limits of the envelope, the spectrum had alternating spectral amplitude maxima and minima, i.e. a rippled pattern. This rippled pattern was also described by a cosine function of the log frequency: the gaps between the neighboring ripples were proportional to frequency. The density of these ripples on the frequency scale is conventionally denoted by the number of periods per octave (oct^{-1}). In this study, the ripple density was always 3.5 oct^{-1}.

For measurements, two signal types were exploited: test and reference signals. The test signal had a rippled spectrum. Every 400 ms the phase of the spectrum ripples was reversed, i.e. one of the spectra in Fig. 1a (spectrum *1*) was replaced with an alternative spectrum (spectrum *2*) and vice versa. The signal contained six segments with alternating positions of the spectral ripples; i.e., the total duration of the signal was 2400 ms. The reference signal had rippled spectrum *1* or *2* (Fig. 1a); one of these two spectra was chosen randomly from trial to trial. The chosen spectrum remained constant during the entire duration of the signal, which was the same as that of the test signal, 2400 ms.

Maskers

The masker spectrum was described by one octave period of a cosine function of the log frequency, i.e., by the same function as the envelope of the signal spectrum. In contrast to the signals, the masker spectrum was not rippled (Figs. 1b–1g). The masker spectra were centered at one of the frequencies from 0.84 to 2 kHz, i.e. from −1.25 to 0 oct relative to the signal at an increment of 0.25 oct. The masker duration was 2400 ms, i.e., the same as the duration of the test and reference signals.

Signal and Masker Generation

The signals and maskers were digitally generated at a sampling rate of 32 kHz. The generation program included white noise (a random digital sequence) filtering by one of the filters, with their shape presented in Fig. 1. The filter output was noise with spectral characteristics specified for the signal or masker. To generate the signals, filters *1* and *2* were used, shown in Fig. 1a; to generate the masker, one of the filters shown in Figs. 1b–1g was used. The onset–offset time during switching on and off as the transition time during the reversion of the phase of the ripples of the test signal was determined by the filter transfer functions. Because of this, no wideband transients occurred during switching on and off or phase shifts. More details on the generation routine were given earlier [11].

The signals and maskers were generated on-line (during the experiment); therefore, the signals or maskers were not identical and differed from trial to trial within the limits of random fluctuations intrinsic in noise.

Experimental Procedure

During the experiments, the listener was in a cabin that attenuated external sounds by 40 dB. The signals and maskers were applied diotically via headphones, i.e., equally to both ears.

A two-alternative forced-choice adaptive procedure was used for the measurements. The following two signals were presented in each trial: test and reference signals; each signal lasted 2.4 s with a 400-ms interval between signals. The order of signal presentation (first test, second reference, or vice versa) varied randomly, trial-by-trial. The listener was asked to detect any periodic modifications in the timbre of the played sound that accompanied the phase shift of the spectral ripples, i.e., to determine which of the signals was the test signal. This formulation of the task was based on the assumption that the phase shift of the ripples can be determined only if the rippled pattern of the spectrum is resolvable, since the signal spectra before and after the phase shift of the ripples were identical with respect to all the parameters except for the phase of the ripples. Since the task included a mandatory choice of one of the signals by the listener, this was a two-alternative forced-choice procedure.

Maskers with a duration of 2400 ms each were applied simultaneously with the test and reference signals. Maskers that accompanied both signals in one trial were identical.

Evaluation of the compression required finding how the threshold sound pressure level of the masker depends on the sound pressure level of the signal. Therefore, each measurement session had a masker level varied with a constant signal level during this session. The procedure was adaptive, because the SPL of the masker in the next trial was established depending on the listener response in the previous trial. A "one–down, three–up" version of the adaptive procedure was used. After three correct detections of the test signal in a row, the SPL of the masker was increased by 2 dB; after each error, the SPL of the masker in the next trial was reduced by 2 dB. The one–down, three–up procedure results in the masker SPL tracking that provides a mean probability of correct responses of $(0.5)^{1/3} = 0.79$ [22]. This is close to the middle of the interval between a probability of 1.0 for errorless detection of the test signal and 0.5 when it is impossible to determine the test signal with correct responses due to random guessing; therefore, the corresponding masker SPL can be taken as the threshold. During measurements, the masker SPL was adaptively varied until ten inflection points (transition from an increase in the masker SPL to a decrease and vice versa) were obtained. The mean value of these ten points was taken as the estimate for the threshold value of the masker SPL in this session.

For each combination of the signal and masker parameters, the measurements were thrice repeated for each of the seven subjects. The mean value of 21 estimates with the corresponding standard error was taken as the final estimate for the threshold value of the masker SPL for this combination of parameters.

RESULTS

The masker threshold levels were measured for two signal values, 50 and 80 dB SPL, and for six positions of the masker frequency band relative to the signal, from –1.25 to 0 oct with a step of 0.25 oct. The results are summarized in Fig. 2.

The threshold level of the masker was minimum during on-frequency masking. It was 58.8 dB for the 50 signal and 87.8 dB for the 80 dB signal. Thus, the threshold level of the on-frequency masker exceeded the signal by 7.8–8.8 dB for both signal values. When the signal level increased by 30 dB (from 50 to 80 dB SPL), a 29.0 dB increase in the masker level at the threshold .

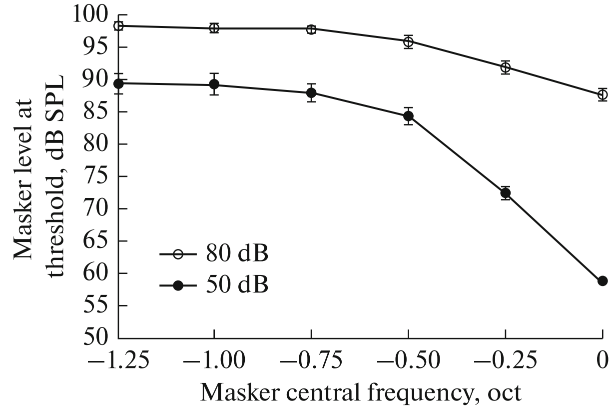

Fig. 2. Dependence of masker level at threshold on position of masker band on frequency scale. Central frequency of masker is given in octaves relative to central frequency of signal. Results are given for two signal levels, 50 and 80 dB, as shown in legend. Error bars are standard errors of the mean.

As the frequency interval between the signal and masker increased, i.e., for a transition from on-frequency to low-frequency masking, the threshold level of the masker increased; i.e., the effectiveness of the masker decreased. For low-frequency maskers 1–1.25 oct below the signal, the threshold masker levels were 89.4 and 89.7 dB SPL for the signal with a level of 50 dB and 98.1 and 98.5 dB SPL for the signal with a level of 80 dB. Thus, as the signal level increased by 30 dB (from 50 to 80 dB SPL), only a 8.7–9.8 dB increase in the masker level at threshold.

We calculated the growth of masking for the on- and off-frequency maskers based on our obtained data. The growth of masking was determined as

$$G = \frac{\Delta T}{\Delta M},$$

where G is the increase in masking, ΔT is the change in the signal level, and ΔM is the change in the masker level. For the experimental data given above, $\Delta T = 30$ dB and ΔM is equal to the difference between the functions in Fig. 2. The growth of masking that we calculated this way increased with an increase in the frequency interval between the signal and masker (Fig. 3). It changed from 1.0 dB/dB for the on-frequency masker (the central frequency of the masker was 0 oct relative to the signal frequency) to 3.3 dB/dB for the low-frequency maskers (the central frequencies of the masker were –1 and –1.25 oct).

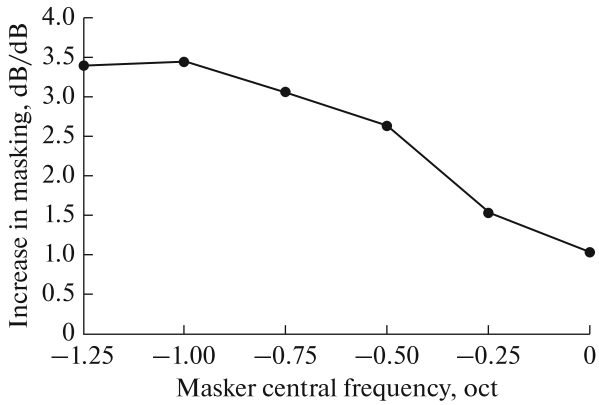

Fig. 3. Dependence of growth of masking on masker central frequency. Frequency is given in octaves relative to central frequency of signal.

DISCUSSION

Evaluation of Compression Using Masking Data

The test on resolution of the pattern of the rippled spectrum that we used in this study revealed a significant difference between increases (in masking and the ratio between the signal level and masker level at the masking threshold) for on- and off-frequency masking. Therefore, the results agree with the data obtained earlier (see Introduction) where masking was determined by detection of a tone signal. As the signal level changed by 30 dB, the masked threshold was achieved by changing the level of the low-frequency masker by less than 10 dB, which can be accounted for by the 0.3 dB/dB compression of the response to the signal, whereas the effect of the low-frequency masker was not subjected to compression. This implies that the on-frequency masker was subjected to nearly the same compression as the signal.

The 0.3 dB/dB compression that we obtained differed from the compression obtained for masking of the detection of a tone signal, 0.16–0.17 dB/dB [5]. However, other studies [6, 7] obtained a compression from 0.2 to 0.4 dB/dB, which is closer to the results of this study. The model that describes the gain in the active mechanism of the cochlea depending on the level of the input signal [23] also predicts 0.28 dB/dB compression within an input signal range e of 50–80 dB for a maximum gain of the active mechanism of 60 dB or 0.4 dB/dB for a maximum gain of the active mechanism of 50 dB. These estimates also agree with the results of the present study. Compression also depends on the frequency of the test signal. Compression in the cochlea is the most pronounced in its proximal part (high-frequency representation) and weakly pronounced in its distal part (low-frequency representation). In psychophysical experiments [7], the compression varied from 1 : 3 to 1 : 5 depending on the signal frequency. Taking all these data into account, we can consider the compression estimates obtained in this study to be within the limits known from previous studies.

Side Effects of Low-Frequency Maskers

When compression was evaluated by masking tone signals, special measures were taken to ensure the absence of side effects of the low-frequency masker (lateral suppression and off-frequency listening), since these effects resulted in underestimation of the compression (see Introduction). These measures were application of forward masking rather than simultaneous masking [5, 24, 25], the use of an additional masker in the expected off-frequency listening frequency range [5], and the use of signals minimally exceeding the baseline threshold [6, 7]. Neither of these measures were applied in this study, since they could not be combined with the applied signal (a signal 1 s in duration with a relatively wide and complex spectrum). Nevertheless, a significant compression effect was obtained. This may be for the following reasons.

(1) Discrimination of signals with complex spectra implies analysis of the ratio of the spectral components in the level range above the threshold. The active cochlear mechanism dominates over the passive one within a wide range of above-threshold levels until its gain is at least a few decibels. Therefore, even if lateral suppression results in some (not too significant) decrease in the gain of the active mechanism, this does not prevent manifestation of its properties including compressive nonlinearity.

(2) Discrimination of signals with complex spectra implies analysis within a relatively wide frequency band. In our experiments, fragmentation of the spectrum (ripple density) was constant over the entire signal frequency band. Therefore, even if the range of best discrimination of the signal was somewhat shifted within the limits of this band due to off-frequency listening, it had little effect on the ability to discriminate the spectral pattern.

Frequency Ranges of Compressive and Noncompressive Effects of Maskers

Since both the signal and all masker versions had a spectral bandwidth of 1 oct, in many cases the masker could not be qualified as strictly on-frequency or strictly low-frequency. The masker could be considered low-frequency if its spectral band did not overlap with the signal band, which occurred at masker band positions of −1 and −1.25 oct relative to the signal band. When the spectral bands of the signal and masker partially overlapped (the band position was from −0.75 to −0.25 oct relative to the signal band), part of the masker spectral band had the effect of low-frequency masking and the rest had the effect of on-frequency masking. The same was correct for the spectral band of the signal: it was partially subjected to low-frequency masking and partially to on-frequency masking. Even when the spectral bands of the signal and masker coincided (0 oct shift), the signal was subjected to partial on-frequency masking and partial low-frequency masking as a result of the effect of the low-frequency part of the masker band on the high-frequency part of the signal band.

The experimental data above demonstrate the integrative effect of the interaction between the signal and masker; in particular, they make it possible to assess the role of compressive effects in these interactions. When the spectral bands of the signal and masker did not overlap (the positions of the masker band were –1 and –1.25 oct relative to the signal band), the high growth of masking (3.3 dB/dB) was evidence of insignificant or zero compression of the masker effect with significant compression of the signal response. When the spectral bands of the signal and masker overlapped insignificantly (the position of the masker band was –0.75 oct relative to the signal band), the growth of masking remained high (3 dB/dB), which was evidence of a predominantly noncompressive effect of the masker. The decrease in the growth of masking to 2.6 dB/dB that we observed for the half-octave overlap of the spectral bands of the signal and masker (the position of the masker band was –0.5 oct relative to the signal band) indicated a notable compressed effect of the masker. However, the growth of masking in this case was also significantly higher than for the on-frequency masker. This made it possible to suggest that discrimination of the signal at this degree of the overlap occurred predominantly in those parts that did not overlap with the masker spectrum and were subjected to noncompressive low-frequency masking. The decrease in the growth of masking to a value that only slightly exceeded 1 dB/dB was observed with significant overlap between the bands of the signal and masker (the position of the masker band was –0.25 oct relative to the signal band). It can be assumed that discrimination of the signal spectrum in this case occurred predominantly in the part that overlapped with the masker spectrum, and the masker effect was subjected to significant compression. Lastly, the decrease in the growth of masking to 1 dB/dB when the spectral bands of the signal and masker completely overlapped indicated that in this case, the interaction between the signal and masker occurred via on-frequency masking.

Thus, it can be concluded that signal discrimination for the test method used in this study occurs depending on the degree of overlap between the signal and masker.

When the spectral bands of the signal and masker do not overlap, signal discrimination occurs under conditions of noncompressive low-frequency masking.

For partial overlap, discrimination occurs predominantly in the part of the signal spectrum t subjected to noncompressive low-frequency masking. It seems that the low-frequency (overlapping with the masker) part of the signal spectrum is effectively suppressed by on-frequency masking, so that the conditions for discrimination remain in the high-frequency (non-overlapping) part of the signal spectrum.

For complete overlap, the effect of the masker is subjected to compression similarly to the signal response.

It was suggested earlier [26] that on-frequency and low-frequency maskers affect the discrimination of the spectral patterns via different mechanisms. This study demonstrates that the difference in the mechanisms may be different manifestations of the effect of compression of the masker depending on the frequency relation between the masker and the signal. This can be an important factor that determines the discrimination of complex signals in background noise.

ACKNOWLEDGMENTS

The study was supported by the Russian Science Foundation, project no. 16-15-10046.

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Translated by E. Berezhnaya