Contribution of Cochlear Compression to Discrimination of Rippled Spectra in On- and Low-frequency Noise

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ABSTRACT

The goal of the study was to assess cochlear compression when rippled-spectrum signals are perceived in noise assuming that the noise might produce both masking and confounding effects. In normal listeners, discrimination between rippled signals with and without ripple phase reversals was assessed in background noise. The signals were band-limited (0.5 oct at a –6-dB level) rippled noise centered at 2 kHz, with a ripple density of 3.5 oct^{–1}. The noise (masker) was band-limited nonrippled noise centered at either 2 kHz (on-frequency masker) or 1 kHz (low-frequency masker). The masker was simultaneously presented with the signals. Masker levels at the discrimination threshold were measured as a function of the signal level using the adaptive (staircase) two-alternative forced-choice procedure. For the on-frequency masker, the searched-for function had a slope of 0.98 dB/dB. For the low-frequency masker, the function had a slope of 1.19 dB/dB within a signal level range of 30 to 40 dB sound pressure level (SPL) and as low as 0.15 dB/dB within a signal level range of 70 to 80 dB SPL. These results were interpreted as indicating compression of responses to both the signal and on-frequency masker and no compression of the effect of the low-frequency masker. In conditions when above-threshold signals are presented in simultaneous noise (the masker), cochlear compression manifests to a substantial degree despite possible confounding effects.

Keywords: hearing, compression, masking, rippled noise

INTRODUCTION

Compressive nonlinearity allows for processing of sound signals over a wide range of levels. To a large extent, compressive nonlinearity appears at the cochlear level. Cochlear compression has been directly revealed by vibration of the basilar membrane (rev. Robles and Ruggero 2001) and by responses of auditory nerve fibers (rev. Sachs et al. 1989; Yates et al. 1990).

In humans, compressive nonlinearity has been demonstrated by psychophysical experiments (rev. Oxenham and Bacon 2004). These experiments implied comparison of masking effects of on-frequency and low-frequency maskers assuming that responses of the basilar membrane to the characteristic frequency (CF) are nonlinear and that responses to frequencies below CF are nearly linear (Robles et al. 1986). Therefore, responses to both a signal and on-frequency masker are equally subjected to compression; when the signal level is varied, the masker level at threshold varies equally. As a result, the on-frequency masker level at threshold linearly depends on the signal level (masking growth is close to 1 dB/dB). Unlike on-frequency maskers, responses to low-frequency maskers in the signal representation are not subjected to compression. Therefore, when the signal level is varied, less variation of the low-frequency masker level is necessary to reach the masked threshold, resulting in masking growth higher than 1 dB/dB. Therefore, a low-frequency masking growth higher than 1 dB/dB indicates compression of

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the response to the signal; the rate of compression is the reciprocal of the masking growth. Using this paradigm, cochlear compression in humans was assessed from 0.16–0.17 dB/dB (Oxenham and Plack 1997) to 0.2–0.4 dB/dB (Nelson et al. 2001; Lopez-Poveda et al. 2003).

To reveal the compression in full measure, precautions were taken to avoid confounding effects that lead to an underestimation of compression. Those confounding effects were lateral suppression and off-frequency listening. Lateral suppression by low-frequency maskers reduces the gain of the nonlinear active cochlear mechanism in the representation of the signal. As a result, the weight of the linear passive mechanism increases and compression becomes less pronounced. Due to the off-frequency listening, the masked signal may be detected in the basilar membrane locus of a higher CF than the signal frequency. In that locus, the weight of the nonlinear active mechanism may be lower than in the signal-CF locus; therefore, the response to the signal may be less compressed. To avoid the effect of lateral suppression, forward, but not simultaneous, masking was used assuming that lateral suppression disappears shortly after the masker offset (Oxenham and Plack 1997). To avoid off-frequency listening, either an additional masker was presented in the frequency band of the expected off-listening (Oxenham and Plack 1997) or near-threshold signals were used to exclude detection outside of the signal-CF locus of the basilar membrane (Nelson et al. 2001; Lopez-Poveda et al. 2003).

The above-mentioned experimental paradigms imply the following specific conditions:

- (i) For the forward masking, the temporal gap between the masker and signal must be adjusted within a narrow time interval where the lateral suppression is no longer effective while the forward masking is still effective.
- (ii) With the use of near-threshold signals, the absolute threshold must be very consistent. Otherwise, the masked threshold cannot be distinguished from the absolute threshold.

Many natural signals do not fit these conditions because of the varying timing and level. When such signals appear in noise, the cochlear compression may be susceptible to influences of both the lateral suppression and off-frequency listening. In addition, for definitely suprathreshold signals, discrimination rather than detection may be of importance. The degree of influence of confounding factors on the cochlear compression may not be easy to predict and must be assessed by direct investigation with the use of stimuli which more or less mimic complex natural signals. The present study was projected as such an investigation.

Specifically, the rippled-spectrum signals were taken as a version of complex-spectrum signals. Similar to many natural sounds, rippled-spectrum signals feature complex-spectrum structure and may be exploited for investigation of complex-signal perception. In normal listeners, resolution of rippled spectra has been investigated in several previous studies (Supin et al. 1994, 1999; Nechaev and Supin 2013; Aronoff and Landsberger 2013).

Both on- and low-frequency maskers deteriorate resolution of rippled-spectrum structure (Supin et al. 2001, 2003; Nechaev et al. 2015). We supposed that on- and low-frequency masking of rippled-spectrum signals may be used to assess the contribution of cochlear compression to perception of complex spectra. So, the particular task of the present study was to measure the on- and low-frequency masker levels at ripple pattern discrimination thresholds to estimate cochlear compression.

METHODS

Listeners and Experimental Conditions

Seven listeners, three males and four females, 20 to 45 years old, participated in the study. For all listeners, audiograms were available. Their hearing thresholds ranged from 0 to 5 dB sound pressure level (SPL) at 1 kHz and from 0 to 15 dB SPL at 2 kHz (1- and 2-kHz frequencies were of particular importance as center frequencies of signals and maskers, see below). The listener sat in a sound attenuating booth MINI 350 (IAC, Germany) providing 40-dB attenuation of external sounds.

The experiments were approved by the Ethics Committee of the Institute of Ecology and Evolution where the study was performed. Sound pressure levels of not more than 100 dB and everyday sound exposure levels (SELs) of not more than 120 dB re 20 μPa^2 s were used to comply with national Sanitary Normative SN2.2.4/2.1.8.562–96. The listener signed an informed consent to listen to the sounds of SPLs and SELs specified above.

Signals and Maskers

The signals were band-limited rippled-spectrum noises (Fig. 1). The envelope of the spectrum of the signal was 1-oct cycle of a cosine function on a logarithmic frequency scale, centered at 2 kHz. Its bandwidth at a –6-dB level was 0.5 oct. The cosine envelope was used to avoid the effects of sharp spectrum edges, which might influence the resolution of ripple patterns (Supin et al. 1998). Within the cosine envelope, there were ripples as a cosine function of frequency logarithm. The ripple density

FIG. 1. Normalized signal and masker spectra. S1 and S2—spectra of 3.5-oct^{-1} ripple density replacing one another in ripple phase reversal signals. On-M and L-M—on- and low-frequency maskers,

respectively. Frequency scale is labeled both in oct re 1 kHz (upper labels) and in kHz (lower labels)

of this ripple pattern was frequency proportional; i.e., the ripple spacing was a constant proportion of the ripple center frequency. Such ripples look equally spaced on a logarithmic scale in Fig. 1. A convenient metric for this type of ripple pattern is the number of ripples per octave (RPO, oct^{-1}). In the present study, the RPO was 3.5 oct^{-1} . A reason to use this ripple density was that at lower densities, the band-limited spectrum contained few ripples such that ripple shifts altered the primary spectrum structure; higher ripple densities resulted in worse resolution of ripple patterns (Supin et al. 1999).

Two signal types were used in the experiments, with and without ripple phase reversals. In the signal with ripple phase reversals, ripples peaks and troughs interchanged (spectra S1 and S2 in Fig. 1). The largest ripples of the two alternative spectra were symmetrically positioned relative to the envelope peak. This ripple position minimized the change in the signal level at the transition from one spectrum to the other. It was assumed that if the ripple pattern was recognizable, this spectrum change could be detected as a timbre change; if the ripple pattern was not recognizable, the spectrum change was not detectable because the spectra before and after the change were identical, except the ripple phase. The test signal lasted 2.4 s; within this time, ripple phase reversals appeared at 0.4-s intervals; i.e., there were three entire cycles of reversals from one of the two alternative spectra to the other and back.

The signal without ripple phase reversals had the same spectrum pattern as one of the two spectra presented in Fig. 1, and there was no spectrum change during the 2.4-s duration.

The spectrum of the masker was a 1-oct wide cycle of a cosine function on a logarithmic frequency scale. The spectrum contained no ripple within its band. The masker spectrum was centered either at the same frequency as the signal (on-frequency masker) or 1 oct below the signal frequency (low-frequency masker), i.e., at either 2 or 1 kHz.

The signal and maskers were digitally generated at a sampling rate of 32 kHz. The generation routine implied filtering of white noise (a random digital sequence) through one of the filters presented in Fig. 1; it was previously described in detail (Nechaev and Supin 2013). The generation routine allowed for the absence of level changes exceeding fluctuation intrinsic in rippled noise (Fig. 2 a1, b1) as well as absence of wide-band transients at signal onsets, offsets, or spectrum changes (Fig. 2a2, b2).

The synthesized signals and maskers were digital-to-analog (D/A) converted via a data acquisition board NI-USB-6251 (National Instruments, Austin, TX), and played diotically through HD580 headphones (Sennheiser, Wedemark, Germany). The range of the frequency-response irregularity of the headphones was not more than 1.5 dB within 0.5-oct bands of the signal and maskers, as measured by a Testo 816 noise level meter (Testo AG, Lenzkirch, Germany) equipped with a 0.5-in microphone that terminated through a 6-cm³ coupler. The sound levels of the signals and maskers were monitored in the same way.

Experimental Procedure

Each measurement trial contained one signal with ripple phase reversals and one signal without rever-

FIG. 2. Waveforms and spectrograms of the signal and masker. **a** Waveforms (1) and spectrograms (2) of the signals. **b** The same of the simultaneous on-frequency maskers. Signals: first with ripple phase reversals (from 0 to 2400-ms time scale), second without reversals

(from 2800 to 5200-ms time scale). Note the absence of signal level change and the absence of spectrum spatters (clicks) when alternative test signal spectra replace one another

sals, each 2.4-s long, with a 0.4-s pause between them (Fig. 2). The order of the signals (first the signal with reversals and then the signal without reversals, or vice versa) randomly varied trial by trial. The instruction to the listener was to report which of the two successively

presented signals, the first or second one, contained periodic timbre modifications, i.e., which of the two signals featured the ripple phase reversals. This experimental design was based on an assumption that with the use of the signals described above, detection

of the timbre modifications and thus discrimination between the two signals was only possible when the rippled-spectrum structures of the signals were resolvable. Thus, the test implied discrimination between the test and reference signals based on their rippled-spectrum structures.

Maskers were 2.4-s long each; equal maskers were simultaneously presented during each of the two signals. For comparison of the effects of on- and low-frequency maskers, evaluation of the masker levels at threshold for a specific signal level is more appropriate than evaluation of signal threshold at a specific masker level. Therefore, masker levels at threshold were evaluated by variation of the masker level keeping signals constant during a measurement run.

A two-alternative forced-choice procedure was used for measurements. The masker level adaptively varied trial-by-trial according to a “three-up, one-down” procedure. After three correct detections of the test signal, the masker level in the next trial was increased by 2 dB; after every mistake, the masker level was decreased by 2 dB. The listener was informed of whether the response was correct or false. This variation brought the masker level to a value resulting in a probability of correct responses of $0.5^{1/3} = 0.79$. The procedure continued until 10 reversal points (transitions from masker level increase to decrease and back) were obtained. The mean of these reversal points was taken as an estimate of the masker level at threshold in the particular trial. For each of the listeners, the measurements were repeated three times. A mean of all repetitions in all listeners was taken as a final estimate of the masker level at threshold for ripple pattern discrimination, with inter-individual standard deviation (SD).

Run by run, signal levels varied from 30 to 90 dB SPL with 5-dB steps. Signals below 30 dB SPL were not exploited because low-level rippled-spectrum signals featured worse sound-pattern resolution (Supin et al. 2005). Signal levels above 90 dB SPL were not exploited because, at higher signal levels, low-frequency masking appeared at masker levels above the allowed limit of 100 dB SPL.

Statistical Analysis

Statistical analysis of the data was carried out using Statistica 10 software.

RESULTS

On-frequency Masker Level at Threshold for Different Signal Levels

On-frequency masker levels at threshold featured low inter-individual standard deviations from $SD = 1.17$ (at

a signal level of 55 dB SPL) to $SD = 3.58$ dB (at a signal level of 30 dB SPL).

Masker level at threshold was nearly linearly dependent on the signal level (Fig. 3a). These levels could be obtained at signal levels from 30 to 90 dB SPL (Fig. 3a). The dependence on signal level could be successfully approximated by straight regression lines: by regression analysis, from $r^2(12) = 0.987$ (listener AL) to $r^2(12) = 0.999$ (listener DN). The slopes of the regression lines varied from 0.958 (listener OL) to 1.016 (listener ES) dB/dB. The mean and SE of these slopes were 0.978 ± 0.008 dB/dB.

The same slope of 0.978 dB/dB was found by regression analysis of the means of masker levels at threshold (Fig. 3b). In this case, r^2 and SE characterized deviation of the means from the straight regression line. The approximation by a straight regression line was satisfactory ($r^2(12) = 0.998$, $SE = 0.015$ dB/dB).

Low-frequency Masker Level at Threshold for Different Signal Levels

Individual masker levels at threshold as functions of signal level are presented in Fig. 4a. At signal levels

FIG. 3. On-masker levels at threshold as a function of signal level. **a** Data for individual listeners. **b** Inter-individual means and SD ; *Trend*—regression line, 1 dB/dB—slope of 1 dB/dB; error bars—inter-individual SD s. Trend statistics: $r^2(12) = 0.998$, $k = 0.978$ dB/dB, $SE = 0.015$, and 95 % confidence interval from 0.945 to 1.011

higher than 85 dB SPL, masker levels at threshold could not be measured in all the listeners because they were beyond the allowed masker level of 100 dB SPL. In listener AL, masker level at threshold could be measured at signal levels at or below 65 dB SPL. In listener ES, masker level at threshold could be measured at a signal level at or above 40 dB SPL. Thus, in as few as five listeners (VK, DN, OF, AM, and OL), such functions could be traced within a range from 30 to 80 dB SPL.

Inter-individual standard deviations for the low-frequency masker were from $SD=0.48$ (for the signal level of 80 dB SPL) to $SD=8.51$ (for the signal level of 30 dB SPL); i.e., deviations were markedly greater than for the on-frequency masker.

Statistical analysis of the results was done for five listeners mentioned above whose thresholds could be measured within a signal level range of 30 to 80 dB SPL. The low-frequency masker level at threshold featured a tendency to nonlinearly dependence on signal level: the higher the signal level, the less steep the dependence of masker level on signal level. These functions could not be approximated by straight regression lines as successfully as data for the on-frequency masker: from $r^2(12)=0.7$ (VK) to $r^2(12)=0.99$ (OL). Therefore, the slopes were separately assessed for signal level ranges from 30 to 40 dB and 70 to 80 dB SPL. Within a signal range from 30 to 40 dB, the slope of the masker level-vs-signal level function varied from 0.41 (DN) to 2.30 (VK) dB/dB. Alternatively, within a signal range from 70 to 80 dB SPL, the slope of the same function varied from 0.02 (AM) to 0.31 (OF) dB/dB. Statistical parameters (r^2 and SE) for these individual slopes were not determined since each of them was obtained by only two experimental points.

The inter-individual mean and SE of the slopes were 0.96 ± 0.78 dB/dB for the signal level range of 30–40 dB SPL and 0.15 ± 0.13 dB/dB for the signal level range of 70–80 dB SPL (Fig. 4b). Likely because of the few number of listeners, with the paired two-tailed t test, the difference between the slopes for the ranges of 30–40 and 70–80 dB did not reach the standard significance criterion: $t(4)=2.27$ and $P=0.086$. By Wilcoxon matched pair test, the difference was significant: $P=0.043$.

On- and Low-frequency Masker Gradient Dependence on Signal Level

To characterize quantitatively the steepness of the functions for on- and low-frequency maskers, their gradients in 10-dB fractions were assessed as functions of the signal level. Figure 5 presents these functions obtained by processing of those from Figs. 3b and 4b, respectively. For the on-frequency masker, the function

FIG. 4. The same as in Fig. 3 for the low-frequency masker. Regression lines are presented for segments of 30 to 40 dB SL and 70 to 80 dB SL signal level (*Trend1* and *Trend2*, respectively)

fluctuated around a value of 1 dB/dB, being never lower than 0.82 dB/dB and never higher than 1.19 dB/dB. For the low-frequency masker, the gradient was 0.97 dB/dB within a signal level range of 30 to 40 dB SPL and

FIG. 5. Gradients of the on- and low-frequency maskers at threshold as functions of signal level. Trend statistics for the on-frequency masker: $r^2(9)=0.38$, $k=-0.005$ dB/dB, $SE=0.002$ dB/dB, 95 % confidence interval from -0.011 to 0.001 dB/dB. Trend statistics for low-frequency masker: $r^2(9)=0.87$, $k=-0.017$ dB/dB, $SE=0.003$ dB/dB, and 95 % confidence interval from -0.023 to -0.011 dB/dB

decreased with signal level increase, falling down to 0.50 dB/dB within a signal level range of 40 to 50 dB SPL and further down to 0.15 dB/dB within a signal level range of 70 to 80 dB SPL.

For these functions, trends were assessed using regression analysis. For the on-frequency masker, the trend of -0.005 ± 0.002 (SE) did not significantly differ from zero ($P=0.076$; 95 % confidence interval from -0.011 to 0.001 , i.e., from below to above zero). For the low-frequency masker, the trend of -0.017 ± 0.003 (SE) was statistically significant ($P=0.0003$; 95 % confidence interval from -0.023 to -0.011 , i.e., significantly negative).

The near-zero trend for the *on-frequency* masker may be considered as an evidence for linear dependence of masker level at threshold on signal level. The negative trend for the *low-frequency* masker may be considered as an evidence for nonlinear dependence of masker level at threshold on signal level.

DISCUSSION

The rippled-spectrum discrimination test demonstrated differences between on- and low-frequency masking. Qualitatively, these differences were similar to those in previous studies (see [Introduction](#)) based on detection of tone signals. Specifically:

- The *on-frequency* masker level at threshold linearly depended on the signal level: the slope of masker level-vs-signal level function was close to 1 dB/dB.
- Alternatively, the low-frequency masker level at threshold exhibited obviously nonlinear dependence on the signal level: from 1.19 dB/dB at low signal levels (from 30 to 40 dB SPL) to 0.15 dB/dB at high signal levels (from 70 to 80 dB SPL).

The nonconstant slope of the masker level-vs-signal level dependence is typical of compression function as has been demonstrated by both physiological (rev. Robles and Ruggero 2001) and psychophysical (rev. Oxenham and Bacon 2004) data. So for signal levels ranged from 40 to 80 dB SPL, the data may be interpreted as a manifestation of compression of the cochlear response to signal. According to this interpretation, changes in the signal level resulted in less change in the cochlear response, while the response to the low-frequency masker was not compressed in the signal representation.

According to this interpretation, the signal compression was not constant across the signal level range of 40 to 80 dB SPL. The functions presented in Figs. 4 and 5 do not allow identifying a breakpoint between compressed and uncompressed parts: the compression rate varied from 0.5 dB/dB for signal levels of

40–50 dB SPL to 0.15 dB/dB for signal levels of 70–80 dB SPL. This range of compression rates covers values obtained by Oxenham and Plack (1997) and Nelson et al. (2001) for 6-kHz tone probes (0.16–0.2 dB/dB) and Lopez-Poveda et al. (2003) (from 0.21 to 0.29 dB/dB, specifically 0.28 dB/dB at 2 kHz). However, those studies featured a breakpoint between the compressed and uncompressed signal levels, which was not characteristic of the present study. It may be hypothesized that this difference appeared because, unlike the tone-detection test, the spectrum-pattern discrimination test required signal analysis within a certain level range. This range might include both compressed and uncompressed parts; with increasing the signal level, contribution of the compressed part increased and contribution of the uncompressed part decreased, thus resulting in deeper compression.

The data presented above were obtained in conditions of simultaneous masking and above-threshold signal levels, i.e., without measures preventing confounding linearizing effects (lateral suppression and/or off-frequency listening). Nevertheless, the experiments revealed deeper compression than experiments with simultaneous masking of the tone signals: approximately 0.5 dB/dB by Bacon et al. (1999) and Hicks and Bacon (1999). We suppose that for our experimental paradigm (spectrum-patterns discrimination test), these confounding processes influenced compression less than for the tone-detection test. The cause of this difference is not known; however, several speculative explanations may be suggested for discussion:

- (i) Discrimination of the complex-spectrum signals occurred due to signal processing within an above-threshold range. Within this range, the active cochlear mechanism may dominate over the passive mechanism until the active-mechanism gain is as high as at least several decibels. Therefore, in the signal-discrimination paradigm, a decrease in the gain within a certain limit due to lateral suppression may not prevent manifestations of properties of the active mechanism, including its compressive nonlinearity.
- (ii) Discrimination of the complex-spectrum signals occurred due to their analysis within a certain frequency band. If statistical parameters of the spectra are constant across this band, a shift in the best signal discrimination along the band due to off-frequency listening may not influence the spectrum resolution.

Nevertheless, contribution of linearizing confounding effects cannot be entirely excluded. To a certain extent, this contribution might be responsible for lower rates of compression at lower signal levels.

Unlike low-frequency maskers, the on-frequency masker is expected to be susceptible to the same compression as the signal. Therefore, 60-dB change (from 30 to 90 dB SPL) in the signal level together with 58.3-dB change (from 37.6 to 95.9 dB SPL) in the on-frequency masker level kept the signal-to-masker ratio at threshold.

In summary, under conditions when the above-threshold signals are perceived in simultaneous noise (the masker), cochlear compression manifested in a substantial degree, although the confounding effects of low-frequency maskers were not excluded.

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COMPLIANCE WITH ETHICAL STANDARDS

The experiments were approved by the Ethics Committee of the Institute of Ecology and Evolution where the study was performed.

Conflict of Interest The authors declare that they have no conflict of interest.

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