


High Ripple-Density Resolution for Discriminating Between Rippled and Nonrippled Signals: Effect of Temporal Processing or Combination Products?

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Abstract

The goal of the study was to investigate the role of combination products in the higher ripple-density resolution estimates obtained by discrimination between a spectrally rippled and a nonrippled noise signal than that obtained by discrimination between two rippled signals. To attain this goal, a noise band was used to mask the frequency band of expected low-frequency combination products. A three-alternative forced-choice procedure with adaptive ripple-density variation was used. The mean background (unmasked) ripple-density resolution was 9.8 ripples/oct for rippled reference signals and 21.8 ripples/oct for nonrippled reference signals. Low-frequency maskers reduced the ripple-density resolution. For masker levels from -10 to 10 dB re. signal, the ripple-density resolution for nonrippled reference signals was approximately twice as high as that for rippled reference signals. At a masker level as high as 20 dB re. signal, the ripple-density resolution decreased in both discrimination tasks. This result leads to the conclusion that low-frequency combination products are not responsible for the task-dependent difference in ripple-density resolution estimates.

Keywords

spectrum-pattern resolution, rippled spectra, masking, excitation-pattern analysis, temporal-processing analysis

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Dependence of Ripple-Density Resolution on Stimulus Parameters

Signals with rippled spectra (in short, rippled signals) are successfully used for measurements of the frequency resolution of hearing. Rippled spectra feature periodically alternating spectral peaks and troughs that form a sort of *spectral grid*. The maximum resolvable ripple density (grid frequency) is a convenient indicator of the spectral resolution of hearing. Unlike the acuteness of equivalent frequency-tuned filters assessed by masking methods (Glasberg & Moore, 1990), rippled test signals allow the characterization of the ultimate frequency resolution resulting both from the acuteness of filters and from a variety of interfilter interactions and other nonlinear processes within the auditory system.

However, estimates of the rippled-spectrum resolution depend on the type of signals and measurement paradigms used. In terms of ripple distribution along the frequency scale, the exploited rippled signals were either linear or logarithmic. Signals with *linearly distributed* ripples have been used in a series of studies of a sensation of *repetition pitch*. This pitch corresponds to a frequency that is equal to the interripple frequency spacing (Bilsen & Ritsma, 1970; Yost, 1996; Yost & Hill,

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1978; Yost et al., 1978, 1996). The repetition pitch was found to appear at ripple densities not higher than 20 ripples/kHz (Yost & Hill, 1978). This limit may be taken as the ripple-density resolution for signals with linearly distributed ripples.

Logarithmically distributed ripples better correspond to the distribution of auditory filter passbands along the frequency scale. For test signals with periodic ripple phase reversals, the ripple-density resolution was found to be 14.9 dimensionless units (a ratio of ripple center frequency to ripple frequency spacing) that corresponded to 10.6 ripples/oct (Supin et al., 1998). For test signals with constant ripple phases, the ripple-density resolution was slightly lower, approximately 8 ripples/oct (Milekhina et al., 2018).

Dependence of Ripple-Density Resolution on Discrimination Task (Rippled or Nonrippled Reference Signals)

The data mentioned previously were obtained in experiments where a rippled test signal had to be discriminated from a rippled reference signal with the same ripple density as the test signal but a different ripple phase pattern. Quite different results were obtained when a rippled test signal had to be discriminated from a nonrippled reference signal. Such discrimination was possible at very high ripple densities: up to 60 ripples/oct by Anderson et al. (2012), 26.1 ripples/oct by Nechaev et al. (2019), and 34.2 ripples/oct by Milekhina et al. (2019). Despite the disagreement in estimates of ripple-density resolution (from 26.1 to 60 ripples/oct), a common result of the mentioned studies was that the resolution assessed by discrimination between a rippled and nonrippled signal was several times as high as that assessed by discrimination between two rippled signals of equal ripple densities but different ripple phase patterns.

Excitation-Pattern and Temporal-Processing Analyses as Possible Mechanisms of Ripple Pattern Resolution

The difference between resolution estimates assessed for different types of reference signal can hypothetically be explained by different degrees of involvement of the two basic mechanisms of frequency discrimination: the excitation pattern and temporal processing. The temporal processing of rippled signals is possible due to their hidden temporal organization: the temporal pattern of the signal repeats at intervals that are a reciprocal of the interripple frequency spacing. In contrast, nonrippled signals do not feature repeating temporal patterns. The temporal organization of signals can be shown in their autocorrelation functions (ACFs). The ACF of a rippled signal with constantly spaced ripples on a linear frequency scale features a peak with a lag that is the reciprocal

of the interripple frequency spacing; the ACF of a band-limited signal with logarithmically spaced rippled features a delayed segment lasting from $1/\delta f_u$ to $1/\delta f_l$, where δf_u and δf_l are ripple spacings at the upper and lower boundaries of the frequency band of the signal, respectively. This segment has a peak at the inverse of the ripple spacing at the center frequency. A delayed ACF peak or segment is not a characteristic of a nonrippled signal. The delay of the ACF peak of rippled signals does not depend on the ripple phase; thus, according to the hypothesis, the temporal-processing mechanism cannot be effective for discriminating between rippled signals of equal ripple densities. In contrast, the difference between the ACFs of rippled and nonrippled signals provides a definite cue for discrimination. The use of this cue may afford the higher ripple-density resolution.

The hypothesis of temporal processing as a cause of the higher ripple-density resolution for discriminating between a rippled and nonrippled signal has been supported by data on the dependence of resolution on signal center frequency (Milekhina et al., 2019) and ripple depth (Supin et al., 2019). For discrimination between two rippled signals, the dependencies that were found were consistent with the excitation-pattern mechanism; for discrimination between a rippled and nonrippled signal, the dependencies that were found were consistent with the temporal-processing mechanism. Nonetheless, the hypothesis cannot be taken as proved until other explanations are rejected.

Combination Products as Possible Mechanisms of Ripple Pattern Resolution

An alternative hypothesis that must be considered involves the combination frequencies produced by complex-spectrum signals. Because of the nonlinear processes in the auditory system, any pair of spectrum components of the primary signal produces combination frequencies. The most prominent combination frequencies are $f_2 - f_1$ (squared products) and $2f_1 - f_2$ (cubic products), where f_1 and f_2 are, respectively, the lower and higher frequencies of the pair. For two-tone stimuli, combination frequencies were demonstrated both in psychophysical experiments (Goldstein, 1967; Plomp, 1965) and in measurements on the cochlear membrane (Robles et al., 1991). A historical review of early investigations of combination tones is presented by Plomp (1965). The combination frequencies are a manifestation of the basic “active” hearing mechanism of the auditory system (Moore, 2013). Rippled noise is a sort of signal that contains many prominent spectral components. All combinations of the spectrum components of the primary signal produce a spectrum of combination products

that may serve as an additional cue for signal discrimination.

Figure 1 shows an example of spectra for rippled and nonrippled stimuli and their combination-product spectra. The example shown is for a 1-octave-wide noise band centered at 4 kHz with a raised-cosine envelope. Signals had a ripple density of 5 ripples/octave (1 and 2) or were nonrippled (3). The steps exemplified in creating this figure were (a) the primary spectra (A) were submitted to an inverse Fourier transform to produce pulse waveforms (B), (b) these waveforms were squared (D) or cubed (F), and (c) the resulting waveforms were Fourier transformed (C and E) to indicate the form of the distortion-product spectra.

The waveforms in B have a central segment that is the same for all of them; this segment determines the octave-wide spectral envelope. The waveforms for the rippled signals have additional segments that, for this example, are centered at ± 1.75 ms re. waveform center; these segments determine the rippled structure of the spectra. For the rippled primary signals, the combination-product spectra are rippled too, although the ripple depth in combination-product spectra is lower than in the primary spectrum; for the nonrippled primary signals, the combination-product spectra are nonrippled. For squared combination products, both waveforms and spectra are identical for (1) and (2), whereas the waveform and spectrum (3) differ from (1) and (2) by the

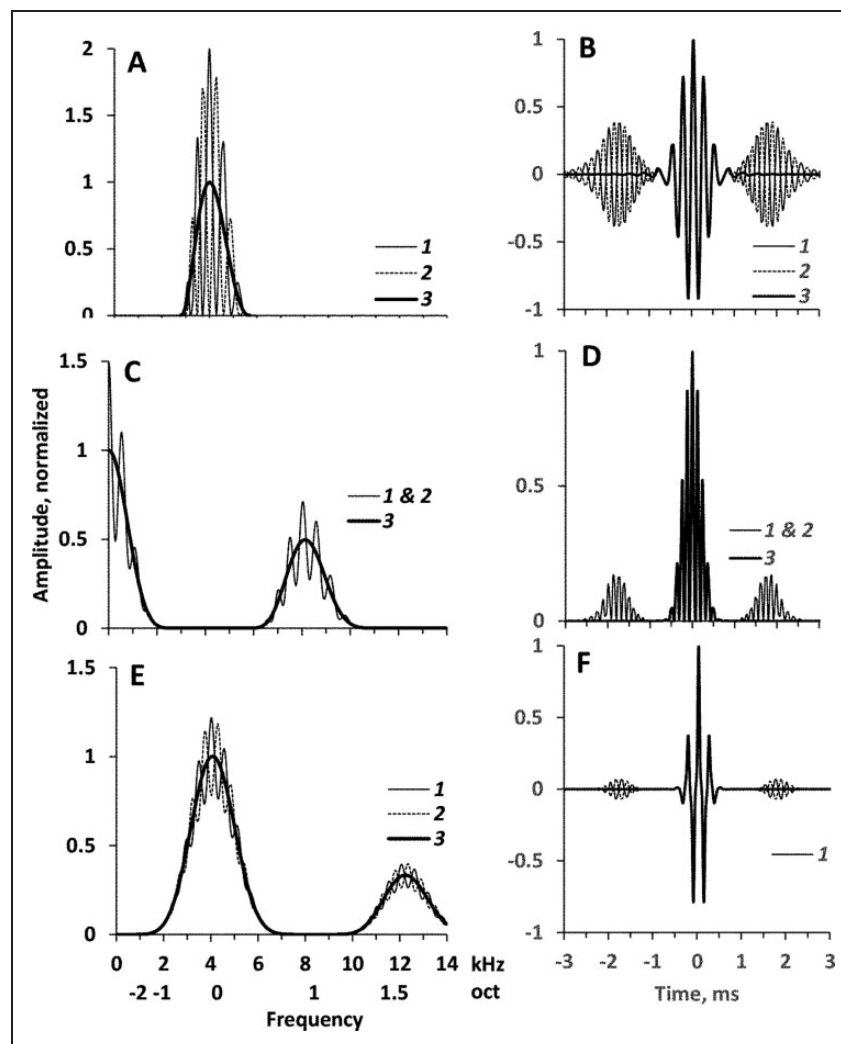


Figure 1. Example of Spectra and Their Corresponding Waveforms Associated With the Primary Stimuli Before and After Squaring or Cubic Distortion, for a 5-ripple/oct Test Signal. A: The primary spectra. B: Their inverse Fourier transforms. C and D show the spectra and waveforms after squaring the waveforms. E and F show the spectra and waveforms after cubing the waveforms. 1 and 2—reference signals with opposite ripple phase, 3—the nonrippled reference signal. For all the spectra, the double frequency scale presents frequency in kHz (upper) and in octaves re. signal centroid (lower). All the waveforms and spectra are normalized re. the maximum magnitude for nonrippled signals.

absence of the additional waveform segment and spectral ripples. For cubic combination products, both the waveforms and spectra are different for signals (1), (2), and (3).

In the context of ripple-density resolution measured using different reference signals, the squared-product spectra deserve the most attention. They contain a low-frequency ($f_2 - f_1$) segment (from 0 to 2.8 kHz in Figure 1) and a high-frequency ($f_2 + f_1$) segment centered at a frequency twice that of the primary signal (8 kHz in Figure 1). The peculiarities of these spectra are (a) the spectra differ between nonrippled and rippled signals; (b) in contrast, the spectra do not differ between rippled spectra of equal ripple densities but opposite ripple phases; (c) below the frequency band of the primary signal, the ripple density as the number of ripples per octave is lower than that in the primary signal; (d) in the low-frequency part of the spectrum, the ripple depth does not decrease with increasing ripple density (Figure 2).

Because of these properties, the low-frequency squared-product spectra might provide a cue for discrimination between a rippled and nonrippled signal but cannot contribute to discrimination between rippled signals of different ripple phases. This property of the squared-product spectra is in agreement with experimental data indicating higher ripple-density resolution for nonrippled reference signals than for rippled reference signals.

Cubic-product spectra contain a $2f_1 - f_2$ segment that has the same center frequency as the primary signal (4 kHz in Figure 1) and a high-frequency segment centered at a frequency three times that of the primary signal (12 kHz in Figure 1). The cubic-product spectra give no preference for distinguishing between a nonrippled and a rippled signal rather than between rippled signals with different ripple phases because (a) these spectra have very low levels at low frequencies where the ripple might be of low density; (b) the ripple phase

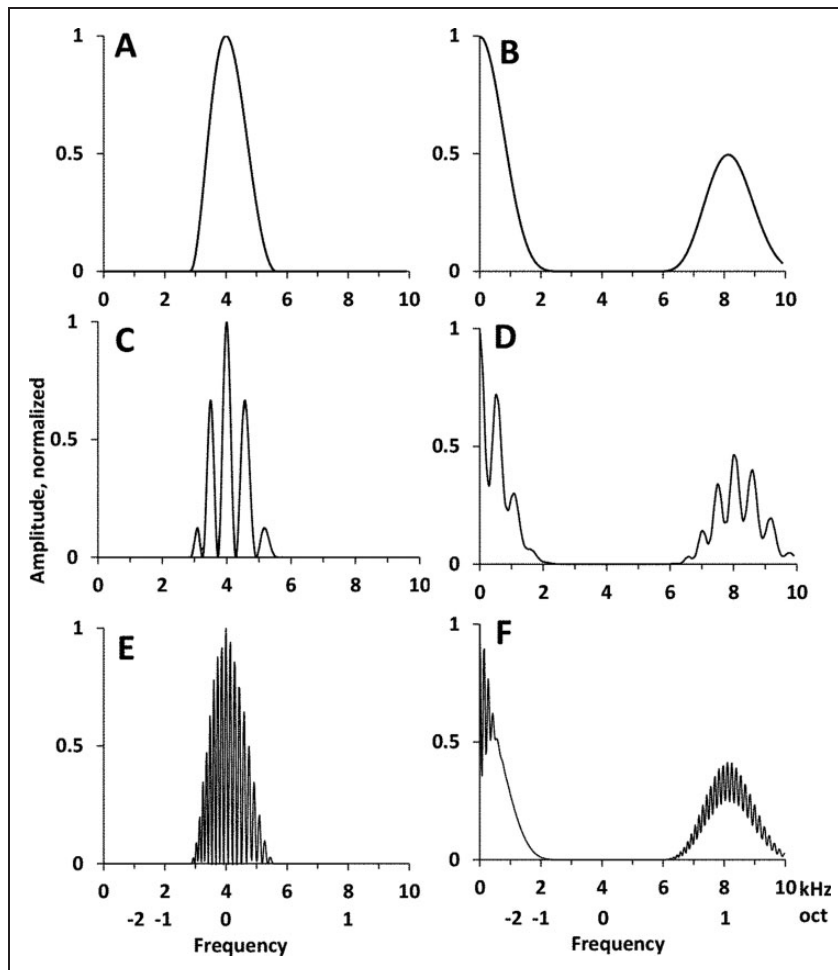


Figure 2. Squared-Product Spectra for Primary Signals Without Ripples and With Ripples of Various Densities. A: Non-rippled signal. B: Squared-product spectrum of this signal. C and D: The same for a signal with ripple density of 5 ripples/oct. E and F: The same for ripple density of 20 ripples/oct.

in these spectra changes when it changes in the primary spectra. The inability of cubic combination products to increase the ripple-density resolution has been noticed earlier (Supin et al., 2001).

Thus, the squared combination products $f_2 - f_1$ might afford increased ripple-density resolution in the task of discrimination between a rippled test signal and non-rippled reference signal. However, it is unknown whether these products *are* the cause of increased ripple-density resolution. Doubt occurs because levels of the combination products are lower than the level of the primary signal. It has been shown (Plomp, 1965) that combination tones are detectable at sensation levels of primary tones mostly 50 to 70 dB; this indicates that the sensation levels of combination tones are 50 to 70 dB lower than those of the primary tones. Using the cancellation technique, Goldstein (1967) and Zwicker (1981) have found that depending on-frequency spacing between primary tones, their phase relations, and level, combination tone levels are 20 to 40 dB lower than levels of the primary tones. It is not known whether the combination product levels are high enough to serve for ripple-pattern discrimination. Therefore, the role of combination products in ripple-density resolution remains unknown.

The role of low-frequency combination products can be assessed by masking the respective frequency band. For that, a masker band should cover the low-frequency combination products but not overlap the primary signal band. If high ripple-density resolution occurs due to the discrimination of combination-product spectra, such masking should reduce the resolution characteristic of discrimination between rippled and nonrippled signals to that characteristic of discrimination between two rippled signals. A masking pink noise in the frequency band of expected low-frequency combination products was used by Narne et al. (2020), although comparison of masking effects depending on discrimination task was not made in that study.

However, effects of a masker that occupies a frequency band below the signal are not limited to masking the combination products. Such a masker may produce low-frequency masking of the primary signal (the effect of upward spread of masking). Due to the upward spread of masking, low-frequency maskers reduce the ripple-density resolution (Milekhina et al., 2017; Nechaev et al., 2015; Supin et al., 2001, 2003). The low-frequency masking of the primary signal must be distinguished from the on-frequency masking of low-frequency combination products. This may be done by comparing masking effects in different experimental paradigms. Low-frequency maskers reduce ripple-density resolution at levels exceeding that of the signal (Milekhina et al., 2017). In contrast, masking of low-frequency combination products might occur at lower

masker levels because (a) lower levels of combination products than of the primary signal and (b) on-frequency masking of combination products in contrast to off-frequency masking of the primary signal. As motivated earlier, low-frequency combination products cannot improve discrimination *between rippled signals* that differ only by ripple phases. In that case, a low-frequency masker affects the ripple-density resolution only by the upward-spreading masking of the primary signal. If the high ripple-density resolution for discriminating *between a rippled and nonrippled signal* occurs *without* the contribution of combination products, the deteriorating effect of low-frequency maskers should appear at the same masker levels as for discriminating between rippled signals. Alternatively, if discrimination *between a rippled and nonrippled signal* occurs due to combination products, much lower masker levels should reduce the resolution.

Yost et al. (1998) have shown that discrimination of rippled signals is affected by higher levels of low-frequency maskers than of on-frequency maskers. It was suggested that the ability to discriminate between two rippled stimuli or between a rippled and a nonrippled signal is unlikely due to low-frequency distortion products and that the effect of the low-frequency maskers occurred due to upward spread of masking. However, the effect of maskers on ripple-density resolution was not quantitatively investigated in that study. Therefore, we used the low-frequency masking paradigm for investigating the role of combination products in the task-dependent difference between ripple-density resolution estimates.

The task of the present study was to compare the effects of low-frequency maskers in two experimental paradigms: discrimination between a rippled signal having periodically reversing ripple phase and a rippled reference signal and discrimination between a rippled test and a nonrippled reference signal.

Methods

Listeners and Experimental Conditions

Six listeners (four males and two females) aged 23 to 39 years old participated in the study. According to standard audiometric tests, all of them had hearing thresholds not higher than 15 dB HL at a frequency of 4 kHz where the signals were centered. During the measurements, the listener sat comfortably in a sound-protecting cabin (MINI 350, IAC, Germany) that provided attenuation of external sounds of not less than 40 dB.

All the listeners signed an informed consent form for participation in experiments involving listening to sounds of sound pressure level (SPL) not higher than 90 dB with an everyday exposure level of no more than

110 dB re $20 \mu\text{Pa}^2$ s. The experimental program was approved by the Ethics Committee of the Institute of Ecology and Evolution where the study was carried out.

Signal and Masker Parameters

We selected the signal and masker parameters considering the following:

1. *Signal bandwidth.* The task of the study was to mask the low-frequency combination products without on-frequency masking of the primary signal. This is possible when the bands of the signal and squared combination products $f_2 - f_1$ do not overlap one another. When the signal has a frequency band extending from f_l (lower boundary) to f_u (upper boundary), the highest $f_2 - f_1$ frequency is $f_u - f_l$. Therefore, the restriction is

$$f_u - f_l \leq f_l \quad (1)$$

From this, it follows that

$$f_u/f_l \leq 2 \quad (2)$$

that is, the signal bandwidth must not exceed one oct. With this restriction, a masker with the upper cutoff at f_l covers the whole frequency band of low-frequency combination products but does not cover the band of the primary signal. Given this restriction, the test and reference signals used in the study were 1 oct wide.

2. *Signal center frequency.* A previous investigation (Milekhina et al., 2019) showed that within a frequency range from 1 to 4 kHz, the higher the frequency is, the higher the difference between ripple-density resolutions for rippled and nonrippled reference signals. Therefore, to achieve a prominent effect in the present study, the center frequency for both the test and reference signals was taken as 4 kHz.
3. *Signal envelope.* To avoid the effects of steep edges of the signal spectra, which may affect the ripple-density resolution (Azadpour & McKay, 2012; Supin et al., 1998), the power-density spectra of both the test and reference signals were enveloped by a raised-cosine function.

Therefore, the test and reference signals had spectra enveloped by a one oct-wide cycle of a raised-cosine function of the logarithm of frequency centered at 4 kHz and extended from 2.8 to 5.6 kHz.

4. *Signal level.* The level of all the signals was taken as 70 dB SPL. This level was reported by the listeners as

comfortable for listening to and discriminating the signals. SPLs of the test and reference signals were equal.

The test signals (Figure 3A) featured spectral ripples that were defined by a raised-cosine function of the logarithm of frequency. The ripple density varied stepwise using the following values: 2, 3, 5, 7, 10, 15, 20, 30, and 50 ripples/oct (a quasilogarithmic scale with six steps per \log_{10} unit). Every 400 ms, the ripple phase in the test signal was inverted, that is, the mutual positions of ripple peaks and troughs on the frequency scale were interchanged. One of the interchanged versions of the rippled spectrum had a peak and the other one had a trough at the center frequency of 4 kHz. The signal contained six segments of alternating ripple phases, so its duration was 2,400 ms. The ripple depth was maximal,

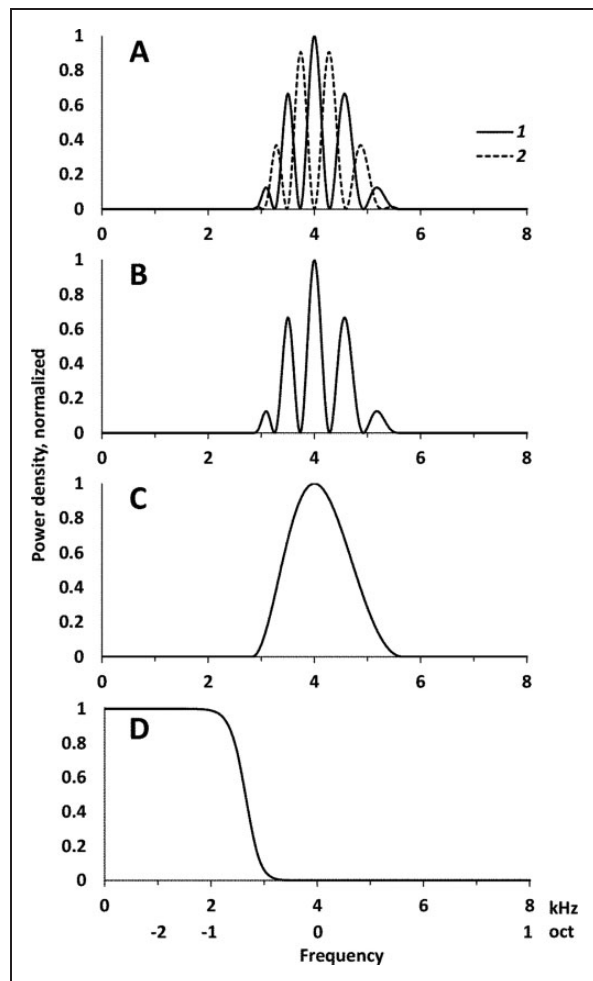


Figure 3. Frequency Spectra of the Signals and the Masker. A: Test signals of a ripple density of 5 ripples/oct; 1 and 2—spectra with opposite ripple phases. B: Rippled reference signal with a ripple peak at the spectrum center frequency. C: Nonrippled reference signal. D: Masker. All spectra are normalized re. maximal spectral amplitude.

that is, in the troughs, the spectrum amplitude fell to zero. The signal had 10-ms rise and fall ramps.

The rippled reference signals (Figure 3B) had the same duration, level, rise–fall time, spectrum envelope, and ripples as those of the test signal. The difference between the test and rippled reference signals was that the reference signals had a constant ripple phase throughout the signal duration. The signal had either a peak or trough at the center frequency of 4 kHz; trial-by-trial, these two versions of the reference signal were used randomly with equal probability. *The nonrippled reference signals* (Figure 3C) had a spectrum that replicated the spectrum envelope of the test signal but with no ripples.

The masker (Figure 3D) was bandlimited noise with an upper cutoff of 2.8 kHz, that is, at the lower boundary of the signal. The masker level varied from 60 to 90 dB SPL, that is, from –10 to 20 dB re. signal level. In pilot investigations, masker levels of –20 dB or lower were found ineffective. The masker burst was 2,400 ms long and was presented simultaneously with each of the signals.

Signal and Masker Generation

All the signals and maskers were digitally generated online at a sampling rate of 32 kHz. The digital generation included the following steps. First, white noise was generated as a Gaussian digital sequence. Then, the white noise was passed through a digital filter. For both the test and reference signals, this was a finite impulse response filter that determined both the spectrum envelope and (when applicable) the ripple pattern. The filter shape was that of the intended spectrum, represented by 8,192 samples, giving a resolution of approximately 3.9 Hz/sample. The impulse response of the filter was the inverse Fourier transfer of the filter shape with a 4096-point circular shift.

For the generation of the test signals, two filters were used with opposite ripple phases. One of the filters had a ripple peak at the center frequency of 4 kHz, whereas the other one had a ripple trough at this frequency. Every 400 ms, the Gaussian digital sequence was redirected from one to the other filter input; the outputs of the two filters were then summed. For the generation of the reference signals, one filter was used: either rippled (for generation of a rippled signal) or nonrippled (for generation of a nonrippled signal). If a rippled reference signal was generated, filters with either ripple peak or ripple trough at the center frequency of 4 kHz were used; trial-by-trial, these two versions of the filter were used randomly with equal probability. For the generation of noise, a low-pass eighth-order Butterworth filter was used. So, the lower limit of the masker was determined by the frequency response of the headphones (see later).

The signals and noise were mixed and digital-to-analog (D/A) converted by a 16-bit D/A converter in an NI-USB 6215 data acquisition board (National Instruments, Austin, TX). The analog signals were played diotically through HD580 headphones (Sennheiser, Wedemark, Germany) which had the low limit of the reproduced frequencies of 12 Hz. The output characteristics of the D/A converter allowed driving the headphones without an additional amplifier and attenuator.

The filter shape and temporal transfer functions were monitored at the interface of the signal-generating program. The acoustic parameters of signals and maskers were monitored by an RA0039 ear simulator (G.R.A.S., Holte, Denmark).

Measurement Procedure

Measurements of ripple-density resolution were performed using a three-alternating forced-choice procedure with adaptive variation of the ripple density. In each trial, the listener heard a sequence of three signals: one test and two reference signals. The two reference signals had equal parameters but were not exact copies of one another, differing by random fluctuations intrinsic in noise. Each signal lasted 2,400 ms, with 400-ms pauses between them. The order of the signals (the test signal was the first, second, or third signal in the sequence) varied randomly trial-by-trial. The task of the listener was to report which of the three signals differed from the two others, that is, to identify the test signal. The listener was not instructed to pay attention to any particular cue that might distinguish the test signal from the reference signals.

The ripple density in the test signal (as well as in the reference signal, if it was rippled) varied adaptively using a two-up, one-down paradigm. After two successive hits (correct identification of the test signal), the ripple density in the next trial increased by one step; after a mistake, the ripple density decreased by one step. This procedure tracked the ripple density to a value that provided a probability of test signal detection of 71% (Levitt, 1971), which is close to the midpoint of 67% between 100% detection and the 33% probability of hits due to random choice; thus, it was taken as the estimate of ripple-density resolution. The reference signal type (rippled or nonrippled) and masker level were kept constant during a measurement run but varied run-by-run. Each measurement run continued until 10 reversal points (transition between ripple density increase and decrease) were obtained. The geometric mean of these 10 reversal points was taken as the resolution estimate for a particular measurement run.

The experimental design did not allow use of the level roving that might be a way to exclude possible level cues. If the levels of all three signals within a trial had varied,

the listeners could not determine which two were the identical reference signals. With equal level and bandwidth of the test and reference signals, the listeners never reported a loudness difference between them.

For each combination of reference signal type (rippled or nonrippled) and masker level, measurements were made three times for each of the six listeners. The mean of the three measurement results was taken as a resolution for the particular listener. The mean of six individual resolutions with the interindividual standard error (SE) was taken as the final estimate of ripple-density resolution for a particular combination of reference signal type and masker level.

Results

Unmasked Ripple-Density Resolution

The unmasked ripple-density resolutions were substantially different between experiments with rippled and nonrippled reference signals. With rippled reference signals, the ripple-density resolution was, on average, 9.8 ± 0.7 (SE) ripples/oct (Figure 4). With nonrippled reference signals, the ripple-density resolution was much higher, on average, 21.8 ± 3.1 (SE) ripples/oct. Thus, the difference between ripple-density resolutions for nonrippled and rippled reference signals was 12.0 ripples/oct, and the ratio was 2.2.

Effects of Maskers

The maskers with a 2.8-kHz upper cutoff frequency reduced the ripple-density resolution. This effect

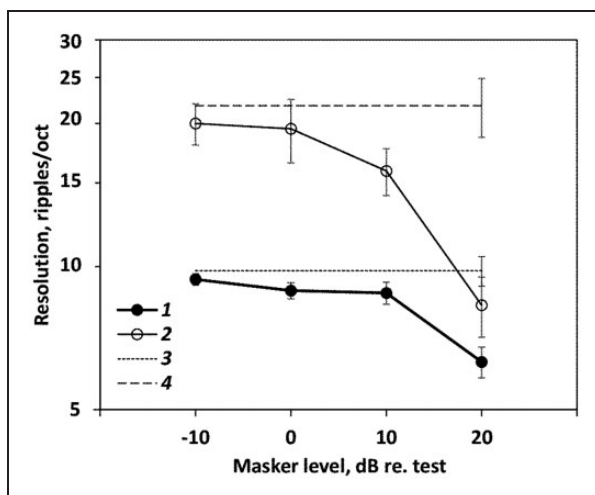


Figure 4. Ripple-Density Resolution Dependence on the Masker Level. 1—data for rippled reference signals, 2—data for nonrippled reference signals, 3 and 4—unmasked resolutions for rippled and nonrippled reference signals, respectively. Error bars: interindividual standard errors of means.

occurred in experiments with both rippled and nonrippled reference signals (Figure 4). The higher the masker level, the more prominent was the reduction effect. For rippled reference signals, the resolution was reduced by 4% (from 9.8 to 9.4 ripples/oct), 9% (from 9.8 to 8.9 ripples/oct), and 10% (from 9.8 to 8.8 ripples/oct) at masker levels of -10 , 0 , and 10 dB re. signal, respectively. For nonrippled reference signals, the reduction was 8% (from 21.8 to 20.0 ripples/oct), 11% (from 21.8 to 19.5 ripples/oct), and 27% (from 21.8 to 15.9 ripples/oct) at masker levels of -10 , 0 , and 10 dB re. signal, respectively. Being expressed as percentage of resolution reduction, the tendency of greater masking effect for nonrippled than for rippled reference signals was not statistically significant ($p = .70$, $p = .66$, and $p = .13$ for masker levels of -10 , 0 , and 10 dB, respectively) as assessed by t test of interindividual variations.

The main distinction between the two conditions at masker levels from -10 to 10 dB re. signal was that the ripple-density resolutions for nonrippled reference signals were higher than for rippled reference signals. The differences were 9.2, 9.1, and 6.1 ripples/oct for signal levels of -10 , 0 , and 10 dB re. signal level, respectively (the ratios of 2.0, 2.1, and 1.7 times). These differences between the two conditions were statistically significant as assessed by t test of interindividual variations ($p = .001$, $p = .01$, and $p = .005$ for masker levels of -10 , 0 , 10 dB re. signal, respectively).

Substantial resolution reduction only occurred for a masker level as high as 20 dB above the signal; the resolutions decreased for both rippled and nonrippled reference signals (by 3.5 and 13.5 ripples/oct, respectively, that corresponded to 35% and 62%). The difference between reduced resolutions for rippled and nonrippled reference signals was not statistically significant as assessed by t test of interindividual variations ($p = .27$).

Discussion

The present study confirmed the difference between estimates of ripple-density resolutions for different discrimination tasks: For the rippled reference signals, the resolution was below 10 ripples/oct, whereas for the nonrippled reference signals, it exceeded 20 ripples/oct. Similar differences were described in a number of previous studies, although the resolution for nonrippled reference signals was even higher than in the present study, from 26.1 to 60 ripples/oct (see above). The cause of varying estimates of ripple-density resolution for nonrippled reference signals is not clear because different studies were performed on different groups of listeners and were not standardized in respect of experimental conditions and methods. Despite the quantitative differences, a common result of all those studies and the

present study is higher ripple-density resolution for non-rippled than for rippled reference signals.

In the context of the task of the present study, a finding that deserves attention is that at masker levels up to 10 dB re. signal, the masking did not eliminate the difference between ripple-density resolutions in two discrimination tasks: The resolution for discrimination between a rippled and a nonrippled signal was substantially and significantly higher than for two rippled signals (9.2 ripples/oct or 2.0 times for a masker level of -10 dB re. signal, 9.1 ripples/oct or 2.1 times at a masker level of 0 dB re. signal, and 6.1 ripples/oct or 1.7 times for a masker level of 10 dB re. signal), whereas for the baseline (no masker) data, the difference was 12.0 ripples/oct and the ratio was 2.2.

Although not eliminating the difference between ripple-density resolutions in two discrimination tasks, low-frequency maskers somewhat reduced the ripple-density resolution. The reduction was not deep but occurred even at a masker level as low as -10 dB re. signal. This effect has been described earlier (Supin et al., 2005). It was interpreted as a result of decreased ripple depth in the excitation pattern because of upward spread of masking. In the present study, this effect tended to be slightly greater for nonrippled rather than for rippled reference signals. This tendency did not reach statistical significance, and the cause of the difference is not clear yet, so we do not discuss it in detail.

Comparison of effects of the maskers on ripple-density resolution at two discrimination tasks (with the use of rippled or nonrippled reference signals) was performed keeping all other experimental conditions constant. So, any factors except the type of the reference signal could not influence the result of comparison.

As motivated above, the combination products cannot serve as cues for discrimination between two rippled signals. The effect of the masker could not arise as a result of masking the combination products. Probably, it was the low-frequency masking of the primary signal. The similar effect of the masker on discrimination between a rippled test and nonrippled reference signal indicated that in this discrimination task, on-frequency masking of low-frequency combination products did not affect the ripple density discrimination either, so the combination products play negligible role too.

At a masker level as high as 20 dB re. signal level, the ripple-density resolution decreased in both discrimination tasks. This effect may be explained by upward spread of masking to the primary signal which results in a reduction in ripple-density resolution for both excitation-pattern and temporal-processing mechanism (Supin et al., 2005, 2019).

The finding that low-frequency combination products do not play a noticeable role in ripple-density resolution leads to the question of why low ripple density in the

combination-product spectra does not help for ripple-density resolution. A possible explanation may be that the level of combination products is too low for such a role. Even for pure tones, the level of combination products is markedly lower than the level of the primary tones (Goldstein, 1967; Plomp, 1965; Zwicker, 1981). For rippled-spectrum signals, there are multiple overlapping combination products of frequency components in the primary signal with variable phase relations. Their amplitudes are hardly predictable but may be supposed to be as low as for tones. Therefore, the role of combination products in ripple-density resolution may be negligible.

Given the finding that combination products do not determine the ripple-density resolution, there is a more realistic hypothesis that explains the task-dependent difference in resolutions by different degrees of involvement of the excitation-pattern and temporal-processing mechanisms of frequency analysis, as has been suggested previously (Anderson et al., 2012; Milekhina et al., 2019; Nechaev et al., 2019).

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