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Spectral prominence influencing the perceived strength of psychoacoustic measures

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Abstract
The perceived strength of many psychoacoustic measures such as roughness, impulsiveness or beating strength all depend to some degree on the overall sound pressure level. In previous studies this effect was mainly observed using different synthetic sounds. In many environmental sounds these psychoacoustic phenomena usually are only present within a certain limited frequency band. For such a frequency band, only a very small change in sound pressure level in relation to the neighboring bands could result in a very large change in the perceived strength of the psychoacoustic measure and thus the dependence of the psychoacoustic measure on the sound pressure level is much stronger than in isolated broad- or narrow-band conditions. This is shown in listening tests where for example modulations were only applied to a limited band within a broadband noise. The level of only this band was then altered in small steps. These changes in the spectral prominence of the modulated band caused a large change in the perceived strength for some psychoacoustic measures. This effect is relevant for environmental sounds such as vehicle interior noise which can exhibit different degrees of spectral prominence. Different approaches for interpreting these data are shown and discussed.
Keywords: Sound, Insulation, Transmission

1 INTRODUCTION

The research that is presented in this contribution was triggered by the observation that two car interior noises with different exhaust systems produced unexpectedly large difference in perceived roughness. In these example noises it was observed that level changes of about 10dB in a certain frequency band caused this unexpectedly large change in roughness of about a factor of 3-4. In previous studies it was shown that a change in level of 40dB results in a change in roughness of about factor three. This holds for both narrow-band and broadband signals [1].
Hence, an increase of the level of a modulated band by 10dB would result in a change in roughness by a factor of approximately 1.3. This theory is not supported by the subjective listening impression, the change in roughness is perceived much higher. This phenomenon can not be explained with previous findings about the level dependency of psychoacoustic roughness. To investigate this effect, an artificial sound reproducing the observations made in the example with environmental recording is introduced. Furthermore this study is extended to extended to the other temporal modulation based perceptual attributes "beating strength" and "impulsiveness" and also "tonality".

2 STIMULI

The the stimuli used for the experiments are based on a pink noise with a sound pressure level of 65dB. For investigating effects for roughness, a frequency band centered around 1kHz and with a width of 3,5 or 7 bark is cut out of the broadband noise. This part is then modulated with a modulation frequency of 70Hz and a modulation depth of -3dB ($20 \cdot \log 10(m)$) and put back into the noise with a level change of -6, -3, 0, 3 or 6dB relative to its original level. This results in 15 different sounds for which the modulated frequency band has a different amount of spectral contrast to the surrounding, unmodulated noise (spectral prominence).
For the phenomenon "beating strength" the sounds were generated with a similar procedure, only the modulation

frequency for the modulated part was set to 4Hz instead of 70Hz. The stimuli for "impulsiveness" were also generated with a modulation frequency of 4Hz, additionally the modulated part was now centered around 1.5kHz instead of 1kHz and the modulating waveform was changed to a sawtooth ("damped") shape. For tonality the band was again centered around 1kHz but instead of modulating the prominent part, a 1kHz pure tone with a level difference of 24dB with respect to the narrow band element was added.

3 PROCEDURE

The strength of the four different psychoacoustic measures is determined by by a parametric adjustment of a reference sound such that it had the same strength of the respective psychometric measure. These points of subjective equality (PSE) were determined in an adaptive staircase procedure where one parameter of the reference sound was varied. The single trials of the adaptive runs for the different prominence parameters were interleaved among each other. For the modulation-based phenomena the reference sound was a pink noise which was modulated in the same way as the narrow-band part in the test sounds. In the adaptive the modulation depth was varied depending on the answers, starting with a change of 4dB, after the first upper reversal reduced to 2dB and finally 1dB after another upper reversal. For tonality the reference sound was also a pink noise but with an 1kHz sinusoid added to the signal. The level of the sinusoid was then altered in the adaptive procedure.
The listener collective consisted of naive listeners who were students at Oldenburg University. The group consisted of two female and six male persons aged between 20 and 26 years (Ø 24 years) for roughness and impulsiveness and of 8 male participants aged between 26 and 30 years (Ø 28 years) for beating strength and tonality.

4 RESULTS AND DISCUSSION

4.1 Roughness

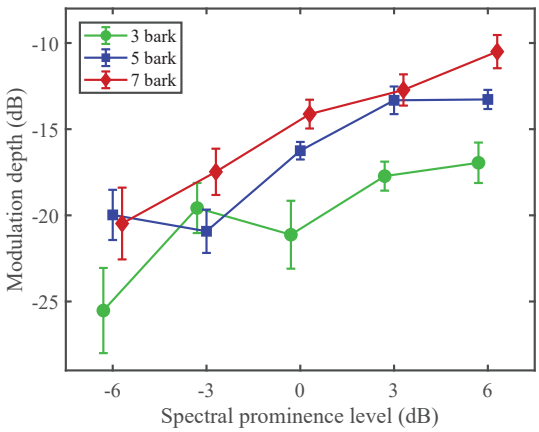

Figure 1. Degree of modulation of the reference sound (y-axis) for equal roughness as the test signals with differing strength of spectral prominence (x-axis) and different bandwidths of the modulated part (colors). The datapoints were slightly shifted on the x-axis for better visibility. The errorbars and datapoints indicate interindividual mean values and standard errors.

In Figure 1 the interindividual mean values for the degrees of modulation of the reference signal adjusted to the same roughness as the 15 test signals are shown. Most important in this Figure is the observation that the perceived roughness increases (as indicated by the modulation depth obtained in the PSE measurement) with

spectral prominence. Note that the only stimulus property that changes is the relative SPL of the modulated stimulus band, but not the modulation strength of the test signal as such. Besides that it is to be expected that roughness will increase for larger bandwidths as can be expected based on previous studies.

The changes in the degree of modulation for different narrow-band level ratios are not in line with the observations made for both narrow- and wide-band signals in previous studies. For example, in the 7 bark condition for a level change of 12dB in the test signals (from -6dB to 6dB) a change in roughness by the factor of 1.4 would be expected from the general level dependency of roughness [1]. From the change in the degree of modulation in the corresponding reference signals a change by the factor of 4.5 is reported [1], so there is a large contradiction between the predicted roughness change in the test signals and the reference signals. While the dependency on the degree of modulation for wide-band signals has already been investigated in studies the effect of changing the level of a modulated narrow-band signal embedded in a non-modulated signal has not been investigated yet. It seems that the change in roughness could not be explained by the effect of level change alone. An additional mechanism seems to cause a large change in roughness for relatively small level changes for these types of signals.

One could argue that these observations may be explained by modulation masking. The reasoning would be that the amount of modulation masking caused by the unmodulated parts of the sound will increase with decreasing spectral prominence level though the fact that this effect should be smaller for the wider bands. This could not be seen in the data. Nevertheless, modulation detection thresholds for the different prominence conditions were measured in an adaptive 3 interval forced choice procedure for five listeners aged between 22 and 36 years. Interindividual mean values are shown in Figure 2. Since there is no significant change in modulation detection threshold for increased prominence levels, the effect of modulation masking seems to be very small and could not explain the large changes in perceived roughness.

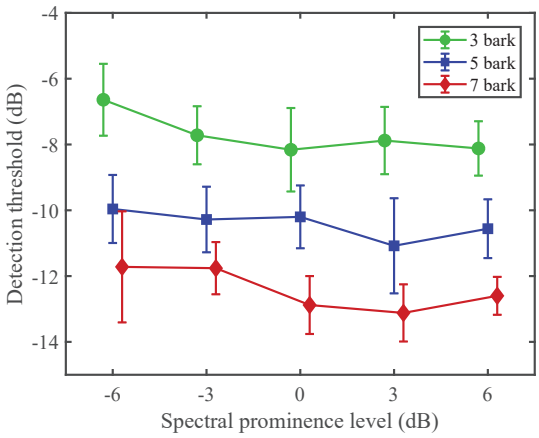

Figure 2. Mean values and standard errors for modulation detection thresholds (y-axis) for different spectral prominence levels (x-axis) and different widths of the modulated band (colors)

In Figure 3 calculated roughness values for the pairs of equal roughness are shown for two different calculation algorithms ([2] and [3]). It is obvious that these calculations do not reproduce the data from the listening test. A reason for this large difference between calculations and subjective ratings could be that the algorithms only account for the level difference but not for the effects found for embedding a modulated signal into a non-modulated signal, i.e. spectral prominence. Figure 4 shows the calculated relative roughness values in comparison to the relative roughness values calculated via the degree of modulation of the reference signal. The latter show a much larger change than the algorithms would predict from the level change.

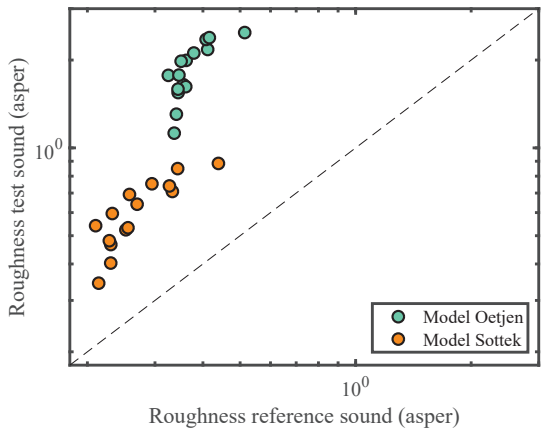

Figure 3. Calculated roughness values for the pairs of equal roughness shown in Figure 1 (x- and y-axis) from two different calculation algorithms (colors). Calculations being in line with the subjective ratings would be close to the dashed line indicating equal roughness.

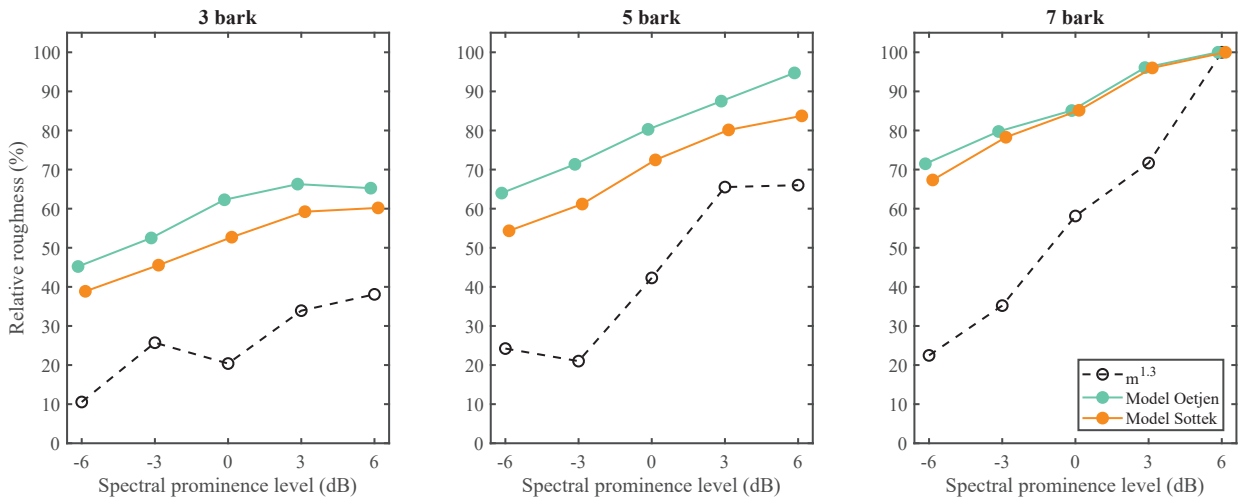

Figure 4. Relative roughness values (y-axis) for the test signals with different spectral prominence levels (x-axis) and different bandwidths (different panels) calculated with two algorithms (colors), compared to the relative roughness of the reference signals calculated from the degree of modulation (black)

A further analysis showed that the algorithms both show a significantly higher dependency on the degree of modulation for broadband noises than the one found in literature. A regression over the datapoints showed that the roughness is proportional to $m^{2.9}$ (Model Oetjen, [3]) and $m^{2.0}$ (Model Sottek, [2]) whereas previous studies suggested a relation proportional to $m^{1.3}$ [1].

4.2 Beating strength

In Figure 5 the degrees of modulation of the reference signal for equal beating strength are shown. The general tendencies are similar to those found for roughness in Figure 1 but the change in modulation depth is slightly lower.

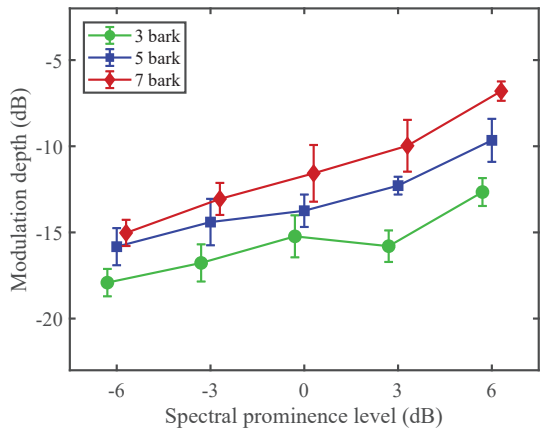

Figure 5. Degree of modulation of the reference sound (y-axis) for equal beating strength as the test signals. The representation is the same as in Figure 1.

Calculating beating strength values for pairs of equal beating strength with the algorithm from "ArtemiS SUITE 8.3" by the Head acoustics GmbH shows, similar to the roughness values, a large difference between the subjective ratings and the calculations (Figure 6). The differences are a bit lower than those found for the roughness calculations.

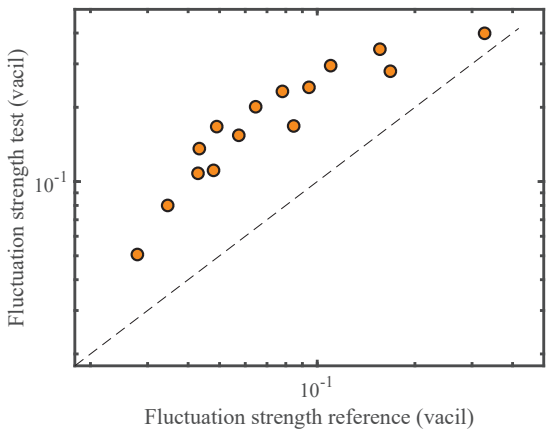

Figure 6. Calculated beating strength values for the pairs of equal beating strength (x- and y-axis) shown in Figure 5. The dashed line indicates the points of equal beating strength.

In this case the SPL of the modulated stimulus part by itself does not seem to be the reason for these differences. Comparing the calculations for the test signals with the beating strength values calculated from the

degree of modulation of the reference signals shows a good correspondence (Figure 7). The calculation method shows, similar to the roughness algorithms, a far too strong dependency on the degree of modulation. From a regression analysis it can be shown that the calculated values are proportional to $m^{2.9}$ whereas previous studies suggested a dependency proportional to $m^{1,0}$ [1].

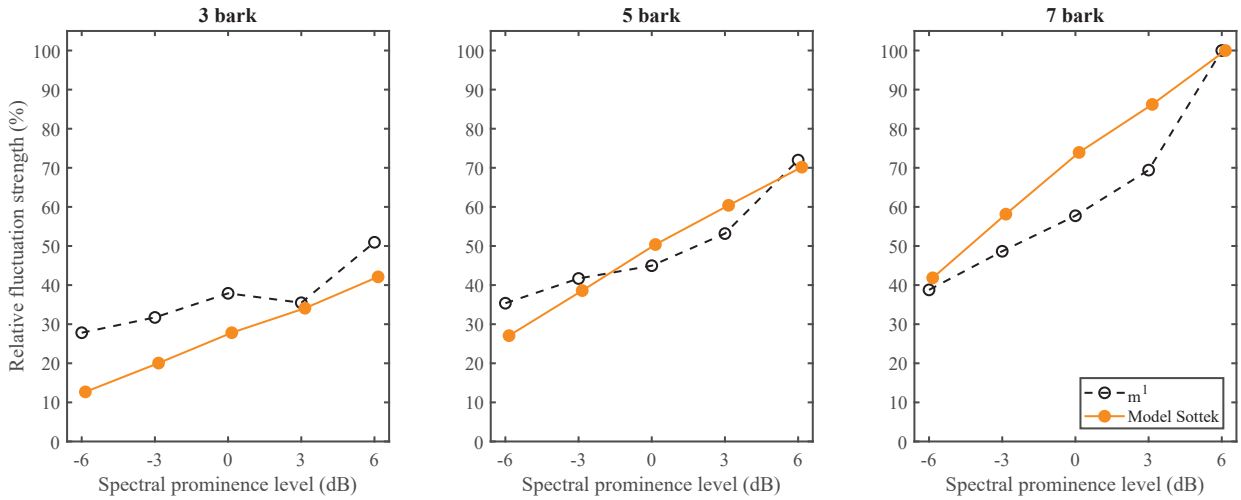

Figure 7. Relative beating strength values (y-axis) for the test signals with different spectral prominence levels (x-axis) and different bandwidths (different panels) calculated with an algorithm (orange), compared to the relative beating strength of the reference signals calculated from the degree of modulation (black)

4.3 Impulsiveness

Similar to roughness the degrees of modulation for equal impulsiveness are shown in Figure 8. These show the same tendencies as the data for roughness and beating strength.

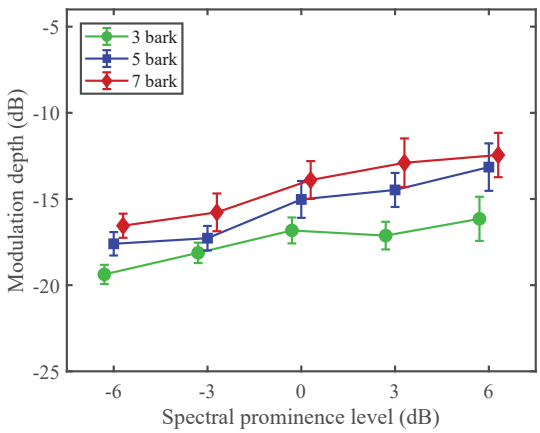

Figure 8. Degree of modulation of the reference sound (y-axis) for equal impulsiveness as the test signals. The representation is the same as in Figure 1.

From an algorithm developed at the University of Oldenburg and from the software "ArtemiS SUITE 8.3" by the Head acoustics GmbH these pairs of equal impulsiveness were calculated. As shown in Figure 9 these calculations differ a lot from the subjective ratings. A further analysis is not possible in this case because there are no fundamental data known from literature.

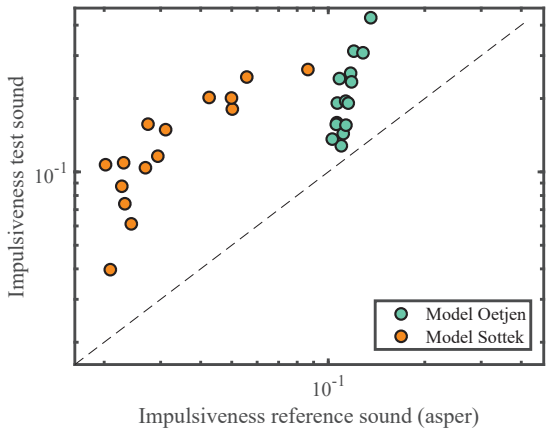

Figure 9. Calculated impulsiveness values for the pairs of equal beating strength (x- and y-axis) shown in Figure 8. The dashed line indicates the points of equal impulsiveness.

4.4 Tonality

In Figure 10 the level differences of the pure tone in the reference sounds for equal tonality are shown. There is no significant influence neither by the bandwith nor by the spectral prominence level. This is in line with the calculation method fronm the German DIN standard for tonality [4].

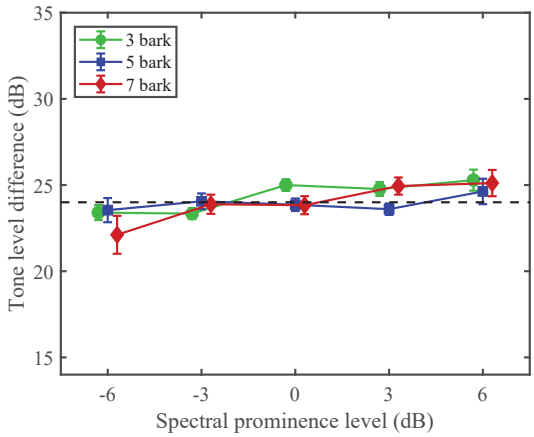

Figure 10. Level difference of the pure tone compared to the noise ground of the reference signal (y-axis) for equal tonality as the test signals. The representation is the same as in Figure 1.

5 SUMMARY

Spectral prominence causes large changes in the perceived expected from the level changes of the modulated stimulus part, both for roughness and beating strength. This phenomenon is much stronger than the change that could be expected from the level change for roughness and beating strength. There is also an effect for impulsiveness but since the general dependency of this measure on the overall level has not been investigated yet it is not possible to quantify the influence of spectral contrast. For tonality this effect could not be observed. This effect is not covered by calculation algorithms for roughness. Additionally, all algorithms for roughness and beating strength show a far too high dependency on the degree of modulation for broadband signals.

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