SUBJECTIVE EVALUATION OF LOUDNESS REDUCTION AND SOUND QUALITY RATINGS OBTAINED WITH SIMULATIONS OF ACOUSTIC MATERIALS FOR NOISE CONTROL

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Abstract: *To improve the outdoor sound quality of cars, in practice different absorbing materials are used which can be constructed with respect to their absorbing character for specific frequency ranges. To simulate such absorbing measures, the spectrum of a Diesel powered car was modified at different frequencies by narrowband (one 1/3-octave band) as well as broadband (up to ten 1/3-octave bands) decreases in 3 dB steps up to 15 dB.*
In psychoacoustic experiments, the influence on the loudness evaluated was assessed. The correlation between the simulated noise control measure and the obtained loudness reduction is discussed. In addition, relations between loudness reduction and ranking of sound quality were studied.

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1 INTRODUCTION

Due to modern absorption techniques, various absorption coefficients can be realized [1]. In the present study, the spectrum of a Diesel powered car was filtered to schematically simulate a broad range of possible absorption properties.

In psychoacoustic experiments, the loudness reduction reached was measured in comparing the spectrally modified sounds with the original sound. Furthermore, the different modified sounds were ranked according to their sound quality by the subjects. An aim of these investigations is to show whether there exists a correlation between the loudness reduction reached and the rank in sound quality evaluation.

2 EXPERIMENTS

2.1 Stimuli

As original sound, the outdoor idling noise of a Diesel powered car was recorded by a dummy head system of HEAD Acoustics positioned at a distance of 2.5 m lateral to the right front wheel at a height of 1.70 m. The 1/3 - octave band spectrum of this original sound is shown below.

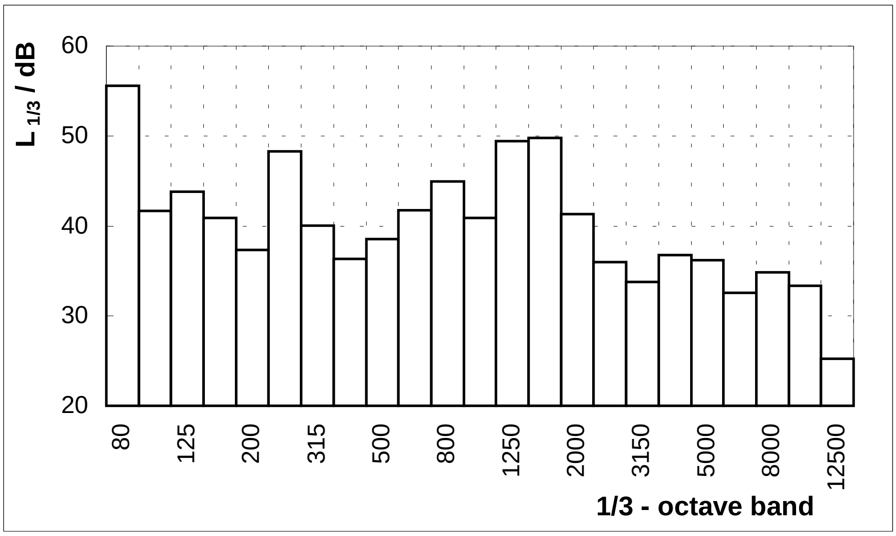

Figure 1: One third octave band spectrum (right channel) of the original Diesel powered car.

To study the effects of acoustic materials for noise control on loudness and on sound quality, the following modifications were realized:

a) Decreases of one single 1/3 - octave band by $\Delta L_{1/3}$ = 3, 6, 9 dB, resp. at 1 kHz, 1.6 kHz, 3.15 kHz, respectively.

b) Decreases of three 1/3 - octave bands by different amounts, whereby the middle 1/3 - octave band is decreased by $\Delta L_{1/3\ m}$ = 3, 6, 9, 12, 15 dB, resp., but the outer 1/3 - octave bands only by $\Delta L_{1/3\ o} = \Delta L_{1/3\ m} / 2$ around 1 kHz, 1.6 kHz, 3.15 kHz, respectively.

c) Decreases of three 1/3 - octave bands by the same amount $\Delta L_{1/3}$ = 3, 6, 9, 12, 15 dB, resp. around 1 kHz, 1.6 kHz, 3.15 kHz, respectively.
d) Decreases of eight 1/3 - octave bands (1 kHz to 5 kHz) and ten 1/3 - octave bands (1 kHz to 8 kHz), resp., by $\Delta L_{1/3}$ = 3, 6, 9, 12, 15 dB, respectively.

All together this results in a sound repertoire of 50 sounds to be evaluated in psychoacoustic experiments.
For the experiments, the sounds were presented in a soundproof booth via a freefield equalized [2] STAX headphone calibrated to reproduce the original sound level.

2.2 Methods

To measure the loudness differences, the method "Magnitude Estimation with anchor sound" was used. Therefore, sound pairs A - B are presented to the subjects with A being always the original sound, assigned with regard to its loudness the value 100. Sound B is any sound of the repertoire and has to be judged regarding to its loudness relatively to sound A.
For the sound quality estimation, the subjects were first instructed as follows: "Please imagine you're going to buy a Diesel powered car for about 80,000 DM. You have now the choice between several cars which are with respect to their appearance and their technical characteristics identically; only the outdoor sounds of the motors differ. Therefore, you like to make your decision dependent on the most convenient sound." In the experiment, the stimuli are represented by capital letters on a monitor and the subjects can listen to them by clicking on the respective letter as often and in any order they like [3]. The task is to arrange the letters in ascending order with respect to the sound quality of the correlated sounds.

2.3 Subjects

The investigations concerning loudness were carried out for the modification a), b) and c) with 8 subjects (3 female, 5 male, median age of 27 years), for the modifications d) with 24 subjects (7 female, 17 male, median age of 24 years). In the experiments concerning sound quality, 9 subjects (2 female, 7 male, median age of 28 years) took part. All the subjects were normalhearing and trained in psychacoustic experiments. Furthermore it was assured that the subjects in every day life could distinguish Diesel powered cars from Otto powered cars.

3 RESULTS

3.1 Loudness

In figure 2 the results of the loudness experiments are displayed for the different decreases (a, b, c and d). Each datapoint is the median with the interquartile ranges of 4 estimations multiplied by the number of subjects. That results for the experiments a), b) and c) in 32 estimates, for experiment d) in 96 estimates.

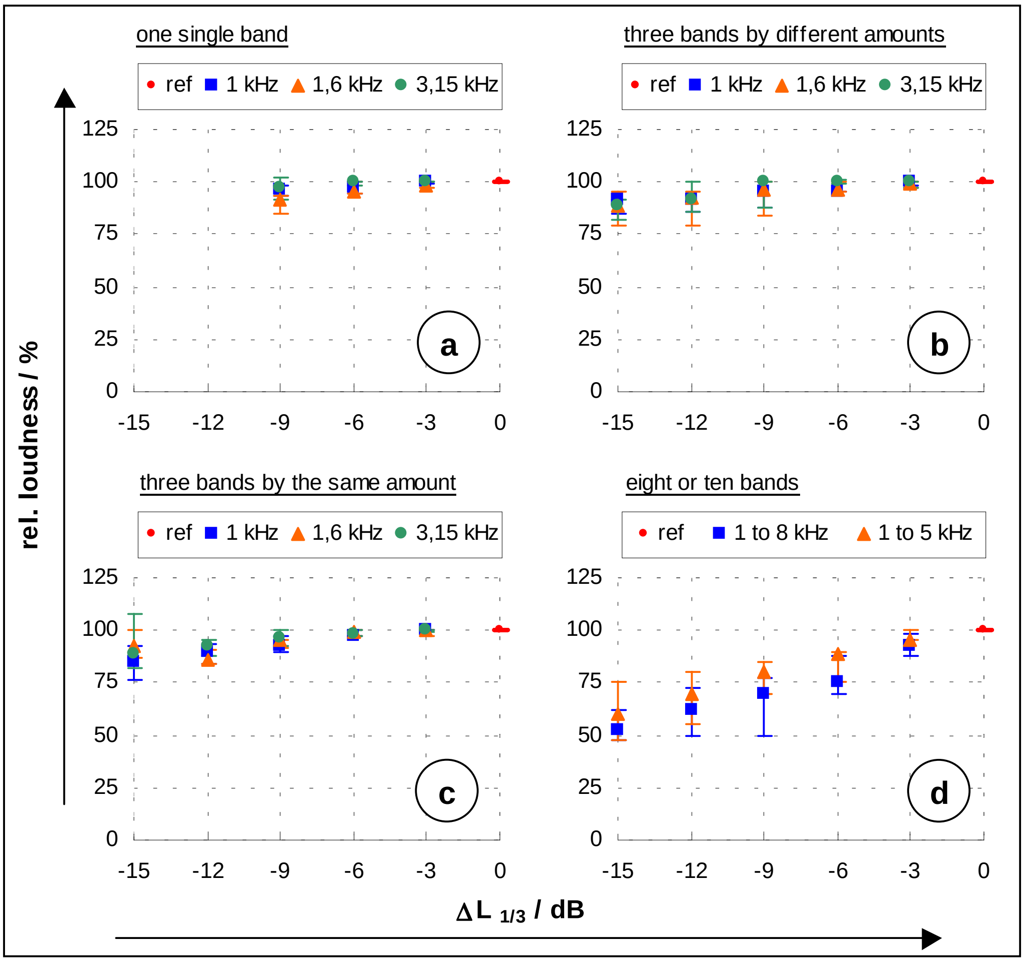

Figure 2: Relative loudness in dependence of the leveldifference in the modified 1/3 - octave band(s) $\Delta L_{1/3}$:
a) decreases of one single 1/3 - octave band,
b) decreases of three 1/3 - octave bands by different amounts,
c) decreases of three 1/3 - octave bands by the same amount,
d) decreases of eight or ten 1/3 - octave bands.

Decreases up to 9 dB in one 1/3 - octave band do not lead to a substantial difference in loudness. With decreases of 15 dB in three 1/3 - octave bands, a loudness reduction of about 20 % can be obtained, no matter whether the three 1/3 -octave bands are decreased by the same or by different amounts. The largest differences can be reached, of course, with the broadband decreases. Even though the median of the modification [1 to 5 kHz] is always above that of the modification [1 to 8 kHz], there is no statistically significant difference (10% level) between the two broadband modifications. On the average, for both broadband modifications a loudness reduction of about 10 % is measured for a 1/3 - octave band level decrease by 3 dB.

2.2 Sound quality

For each kind of modification (e.g. decrease of eight 1/3 - octave bands), the subjects had the task to rank the stimuli with respect to their sound quality. Hence, for modifications of one single 1/3 - octave band they had to arrange 4 sounds (reference, -3 dB, -6 dB, and -9 dB) on 4 ranks (1st rank: best sound quality, 4th rank: worst sound quality), for the other modifications 6 sounds had to be ranked (reference, -3 dB, -6 dB, -9 dB, -12 dB, and -15 dB).

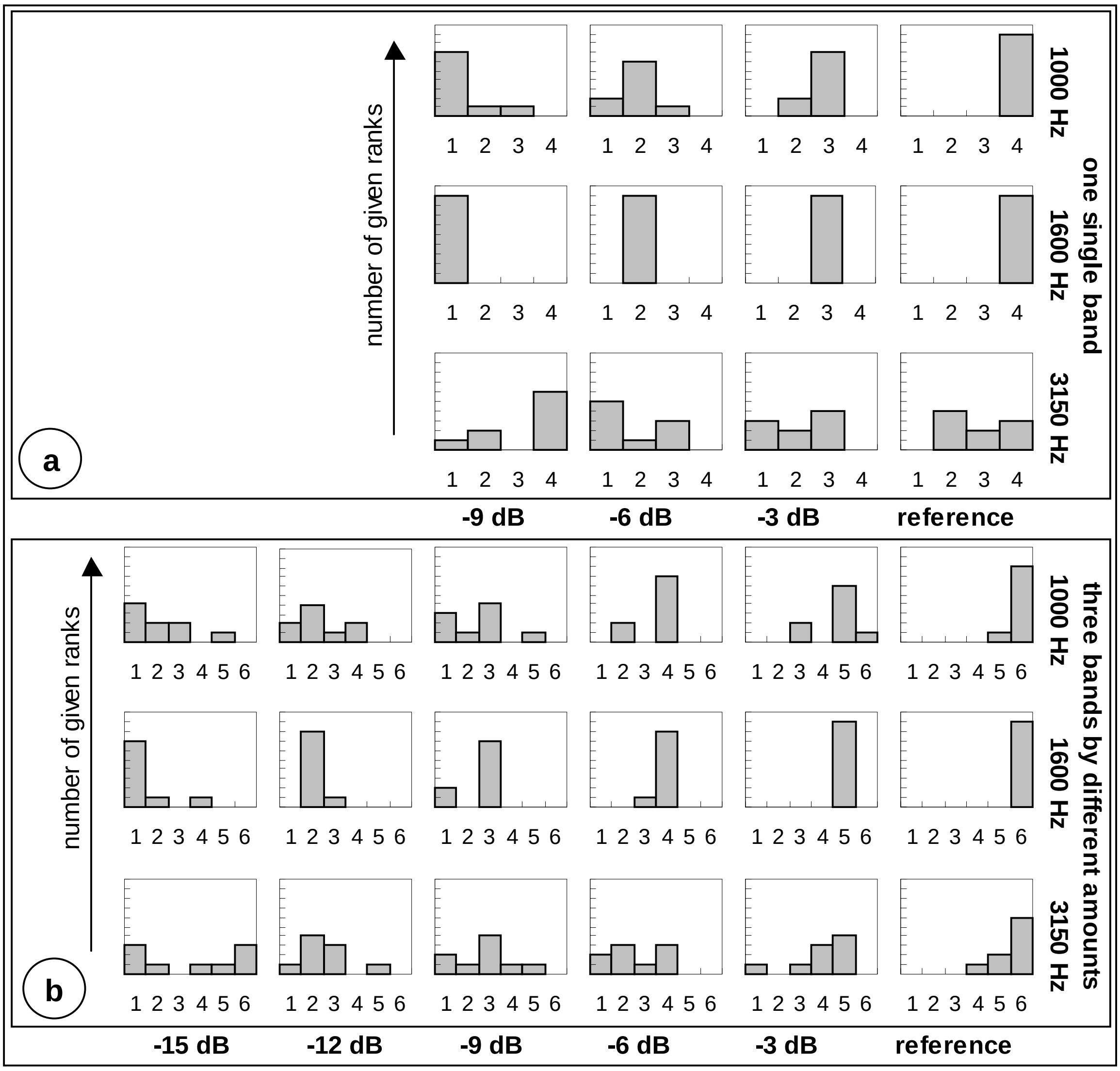

Figure 3 a) and 3 b): Ranking for decreases of one single 1/3 - octave band (a) and for decreases of three 1/3 - octave bands by different amounts (b).

In figure 3 a) to d) the resulting rankings of all modifications by the nine subjects are displayed. Thus, for a decrease of the 1/3 - octave band at 1000 Hz by 9 dB for example, the

following distribution resulted: seven subjects ranked that sound on the 1st rank, one subject on the 2nd and one subject on the 3rd rank (upper left inset in figure 3 a)).
Figure 3 a) shows the rankings for the decreases of one single 1/3 - octave band. For the decrease of the 1/3 - octave band at 1600 Hz, the 9 subjects agreed perfectly that the sound quality is improving if the 1/3 - octave band is decreased. This tendency is also observable for a decrease of the 1/3 - octave band at 1000 Hz. However, a decrease of the 1/3 - octave band at 3150 Hz does not necessarily lead to an improvement in sound quality. In contrast, most subjects estimated in this case the sound with the largest decrease as worst.
Figures 3 b) and 3 c) show the rankings for the modifications of three 1/3 - octave bands. For decreases of the three bands by different amounts (b) the same tendency as for decreases of one single 1/3 - ocatve band is visible: obvious preference of sound quality by a decrease of the 1/3 - octave bands around 1600 Hz, the trend of better sound quality by a decrease of the 1/3 - octave bands around 1000 Hz, and a more scattered distribution for a decrease of the 1/3 - octave bands around 3150 Hz. Thus, a decrease of 15 dB in the 1/3 - octave bands around 3150 Hz leads even to a distribution with two faraway lying maxima (1st and the 6th rank).

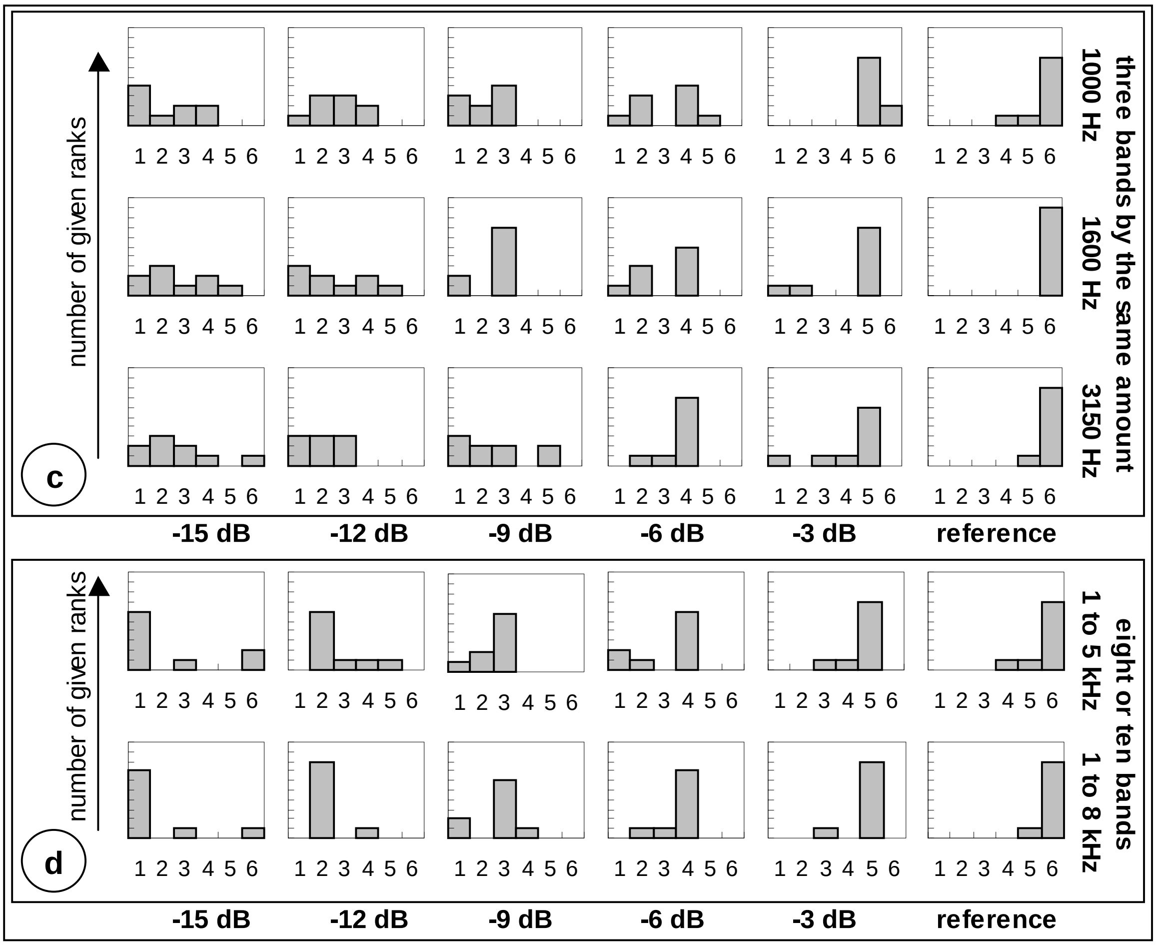

Figure 3 c) and 3 d): Ranking for decreases of three 1/3 - octave bands by the same amount (c) and for decreases of eight or ten 1/3 - octave bands (d).

For the decreases of the three 1/3 - octave bands by the same amount (c), subjects nearly agree that for the sounds with small decreases (3 dB, 6 dB) 3 dB mean an improvement in sound quality of 1 rank. However, the sounds with decreases of 9, 12, and 15 dB compete for the better ranks: a more scattered distribution occurs.
Figure 3 d) displays the results for the decreases of eight or ten 1/3 - octave bands. For both bandwidths, the trend of better ranked sound quality for sounds with larger decreases can be observed.
However, it should be mentioned that there are also subjects, who estimate the sounds with decreases of 15 dB as the sounds with the worst sound quality.
To give a better overview of the ranking results, figure 4 shows the median with the interquartile ranges calculated of all of the ranks given by the subjects for each modification. Thus, the subjects' agreement for the sounds with modifications at 1600 Hz or broadband modifications emerges in continuous curves and partly nonexistent interquartile ranges, the disagreement and the more splitted opinions regarding the modifications at 3150 Hz show up in the up-down-trends of the curves and the larger interquartile ranges.

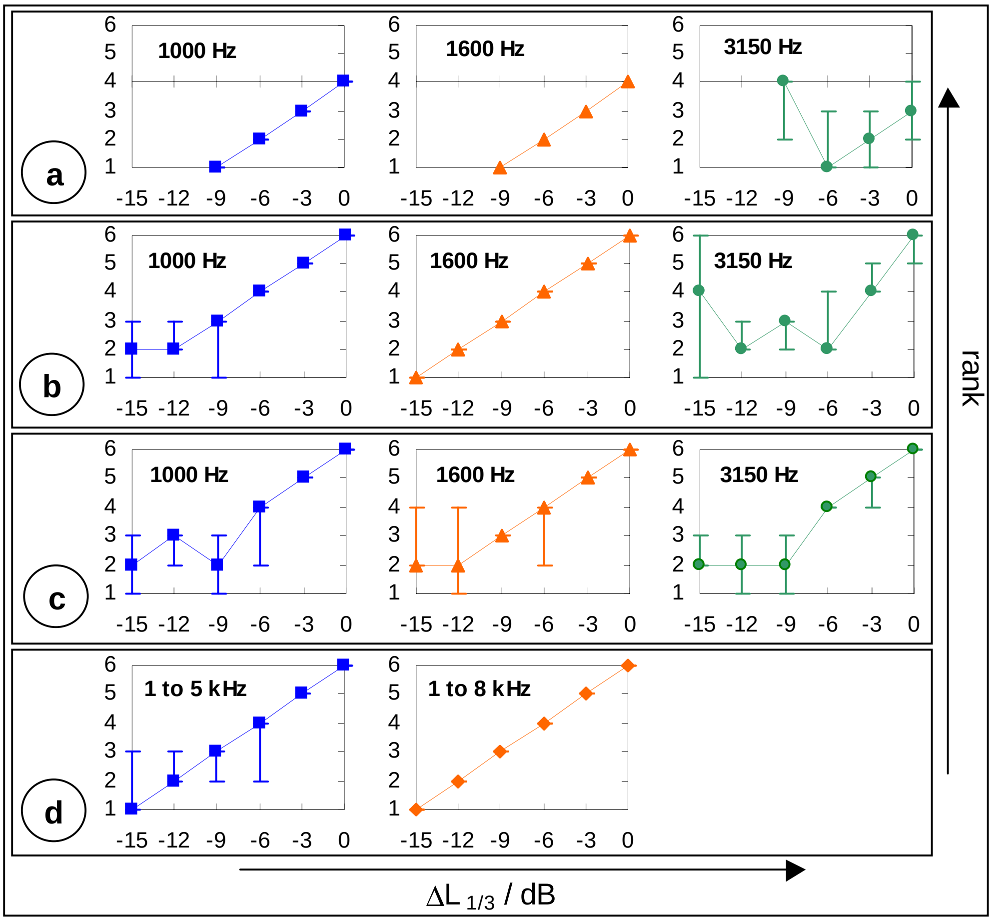

Figure 4: Median and interquartile ranges of the rankings.

4 DISCUSSION

4.1 Loudness

Regarding the results of the loudness investigations, it can be stated that decreases of one single 1/3 - octave band - no matter in which of the frequency ranges investigated - do not lead to statistically significant differences. For decreases of three 1/3 - octave bands, no statistically significant difference between the two versions investigated (b or c) can be seen. Furthermore, in this case, the frequency range does not influence the results for loudness statistically significantly. For broadband decreases no statistically significant difference between eight or ten decreased 1/3 - octave bands can be measured.

Those slight effects on loudness for a decrease of only one 1/3 - octave band as well as the slight differences between the two different middleband modifications are in good agreement with the model of masking patterns [2, 4]. Hence, one single decreased 1/3 - octave band can be easily filled up by the lower and upper flanking specific loudness and also the difference between three unequally and equally decreased 1/3 - octave bands leads to relatively small differences in the respective masking patterns.

4.2 Sound quality

In spite of very similar results for loudness, the subjects if asked for the sound quality, rank the sounds according to the kind of modification and the respective frequency range very differently.

If the 1/3 - octave band distribution of the original sound is recalled and the manipulated frequency ranges are compared therewith, it becomes evident that a decrease at 1600 Hz would clip a peak, whereas the 1/3 - octave bands at 1000 Hz or 3150 Hz show a minimum in the 1/3 - octave band distribution of the original sound (figure 5).

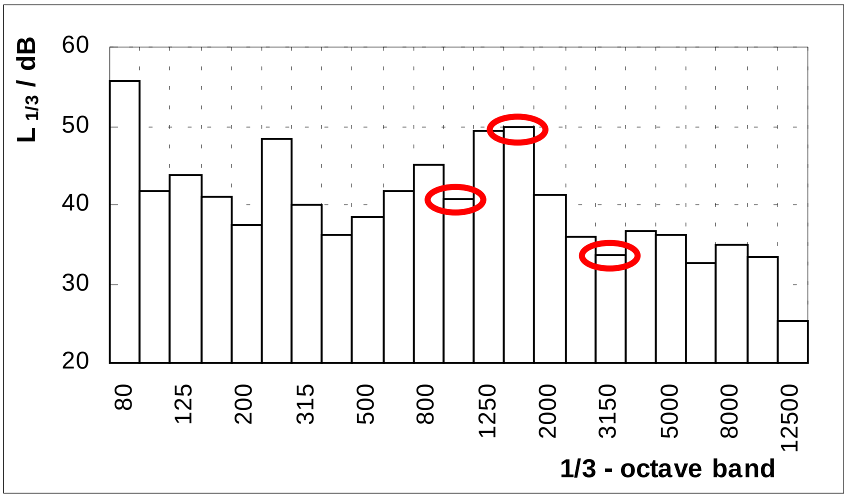

Figure 5: 1/3 - octave band spectrum of the original sound (right channel) with the manipulated frequency ranges indicated by red circles.

Hence, a decrease at 1600 Hz might subjectively lead to almost the same loudness reduction as a decrease at 3150 Hz, but it may result in a different timbre which may lead the subjects to judge the sound quality differently. According to those results it seems reasonable to recommend a decrease of frequency ranges which are sticking out of the spectrum. However, for decreases in a frequency range with a minimum in the spectrum, a closer view on the situation has to be taken: a decrease could result in an improvement of sound quality (in our case for decreases at 1000 Hz) as well as in a deterioration (in our case for decreases at 3150 Hz).

4.3 Loudness / sound quality

To obtain a better impression of the relations between the estimated loudness and the ranking of sound quality of the sounds, in figure 6 medians of the loudness evaluations are faced to the medians of the ranks given. In many cases, the sounds seem to be ranked according to the loudness reduction, except for the modifications at 3150 Hz. In this case, subjects seem to make their decision on other aspects, as for example the timbre of the sound or how suitable the sound is for the product [5].

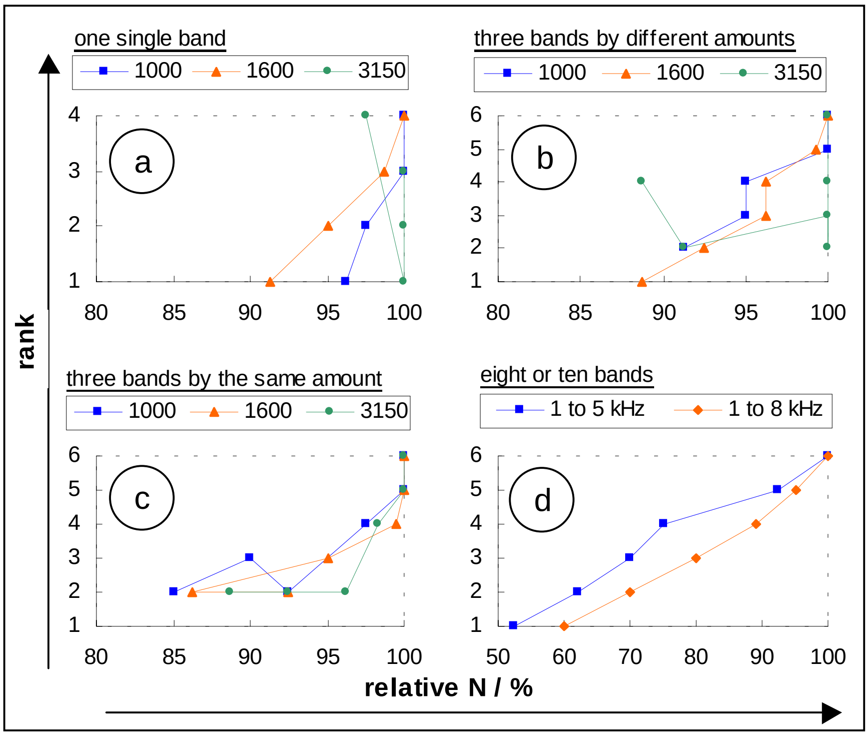

Figure 6: Correlation of the estimated loudness and the given rank (only medians).

5 CONCLUSION

To improve the outdoor sound quality of idling Diesel powered cars, it is reasonable to reduce the loudness of the sound by absorbing measures. As a rule, broadband decreases show a strong correlation between the loudness reduction reached and the improvement in sound quality. However, when decreasing one to three 1/3 - octave bands, attention should be given to the frequency range, which the measure effects: a decrease of a spectral maximum will improve the sound quality, whereas a decrease of a minimum proved to be a more complex matter. Hence, based only on the spectrum, a clear prediction whether a decrease of the respective 1/3 - octave band will result in an improvement in sound quality, is not always possible. The ultimate effects in sound quality can be clarified best by psychoacoustic experiments.

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