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Interdependencies of Humming, Rumbling and Booming

Florian Doleschal, Gloria-Tabea Badel, Jesko Verhey

Department of Experimental Audiology, Otto von Guericke University Magdeburg

*florian.doleschal@med.ovgu.de

Abstract
Humming, rumbling and booming are sensations that require the presence of low-frequency tonal components in the noise. If it only contains a low-frequency tone the sound is perceived as humming, if this component is modulated it is perceived as rumbling and if more tonal components with higher frequencies are present that are related to the low-frequency tonal component (e.g. are harmonics), the sound is perceived as booming. Sounds eliciting these sensations are often observed in vehicle acoustics when downspeeding the engine, which is a strategy to reduce fuel consumptions in vehicles with combustion engines. The present study investigates how these sensations interact using original sounds from the vehicle interior and sounds where parts of the spectrum are altered to change the magnitude of the sensations. The results show that the three sensations correlate in some aspects. Furthermore, dominance effects have been observed, so that measures to manipulate a certain sensation do not take effect if another sensation is much more pronounced.
Keywords: Rumbling, Humming, Booming, Interdependencies

1 Introduction

Running combustion engines at lower speeds is a common approach to improve the fuel efficiency of passenger vehicles. At these low engine speeds, low-frequency sensations, such as humming, rumbling and booming, are often associated with the vehicle interior sound and can severely reduce its pleasantness [1]. While the sensation of humming is elicited by the appearance of tonal components in a frequency range below 100 Hz, the sensation of rumbling involves additional amplitude modulations. The sensation of booming is an interaction of low- and medium-frequency components, where the modulation frequency of the medium-frequency components is the same as the audio frequency of the low-frequency component [1]. Even though, the sensations involve some common signal properties and therefore imply certain interdependencies, the terms humming, rumbling and booming are commonly used interchangeably with different meanings [1, 2, 3]. Therefore, an experiment was set up, where the three sensations were evaluated for the same set of stimuli, which involve both original recordings and recordings with spectro-temporal manipulations [4]. The results show, to which extent the sensations are interdependent of each other and if certain sensations are dominant.

2 Experiment

2.1 Introduction phase

Many listeners are not familiar with the exact meaning of the terms humming, rumbling and booming in the context of vehicle sounds. Therefore, an introduction phase was included in the experiment, where both artificial and recorded vehicle interior sounds were presented to the listeners to familiarize them with the sensations. The synthetic sounds (see Figure 1) contain key features of the sensations, which have been determined by a previously conducted experiment with experts in vehicle acoustics. The humming introduction sound consists of a single 50-Hz sinusoid. In contrast, the rumbling sound is an amplitude modulated 40 Hz sound with a modulation frequency of 8 Hz. The resulting sound therefore consists of three sinusoids, a 40-Hz sinusoid and two sinusoids with frequencies of 32 and 48 Hz. As mentioned before, booming is an interaction of low- and medium-frequency components. Therefore, the introduction sound for the sensation booming consists of a low-frequency sinusoid at a frequency of 38 Hz and higher frequency components with frequencies of 152 Hz, 304 Hz, 456 Hz and 608 Hz, which are modulated at a rate of 38 Hz.

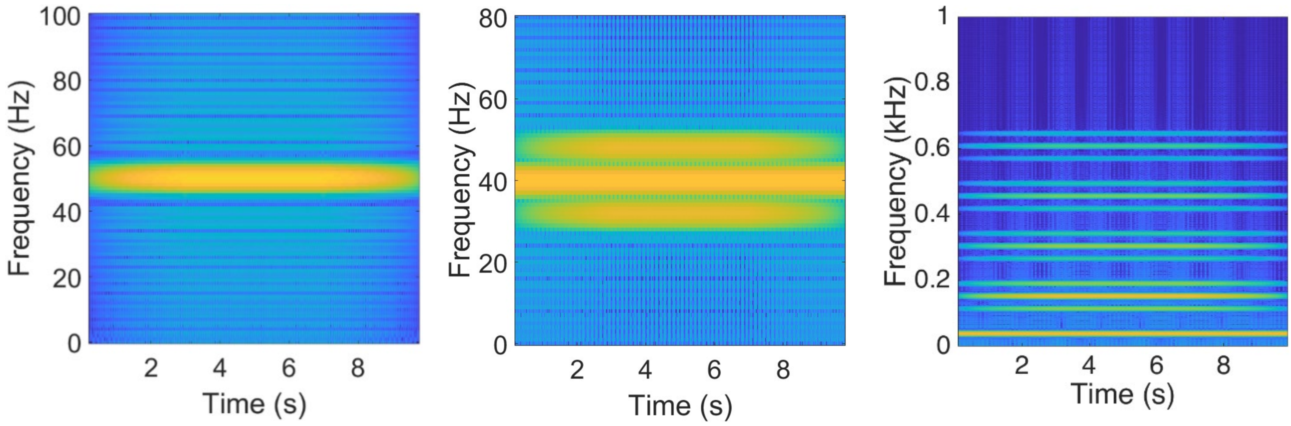

Figure 1: Spectrograms of the introduction sounds for the sensations humming (left panel), rumbling (center panel) and booming (right panel).

In addition to the synthetic introduction sounds, for each sensation, one recorded sound, which strongly elicited the respective sensation and one sound, which did not elicit any of the three sensations (see Figure 2), were presented. The presented sounds have been determined by experts in the field of vehicle acoustics and were not part of the stimuli set of the main experiment. The sound, whose spectrogram is displayed in the first row of Figure 2, strongly elicited the humming sensation, due to the dominant low frequency components at frequencies of 50 Hz and 100 Hz. The sound of the second row contained a low-frequency component at a frequency of about 30 Hz with audible amplitude modulations, eliciting a rumbling sensation. The third sound involves a low-frequency component and several modulated higher-frequency components, eliciting a strong booming. The last sound was of a noisy character and did not elicit any of the three sensations. Therefore, it was presented as a counterexample of a sound eliciting the respective sensation.

All sounds were switched on and off using raised-cosine ramps with a duration of 10 ms. The listeners were allowed to listen to both the artificial introduction sounds and the recorded introduction sounds until they were familiar with the sensation. Then, they started the main experiment.

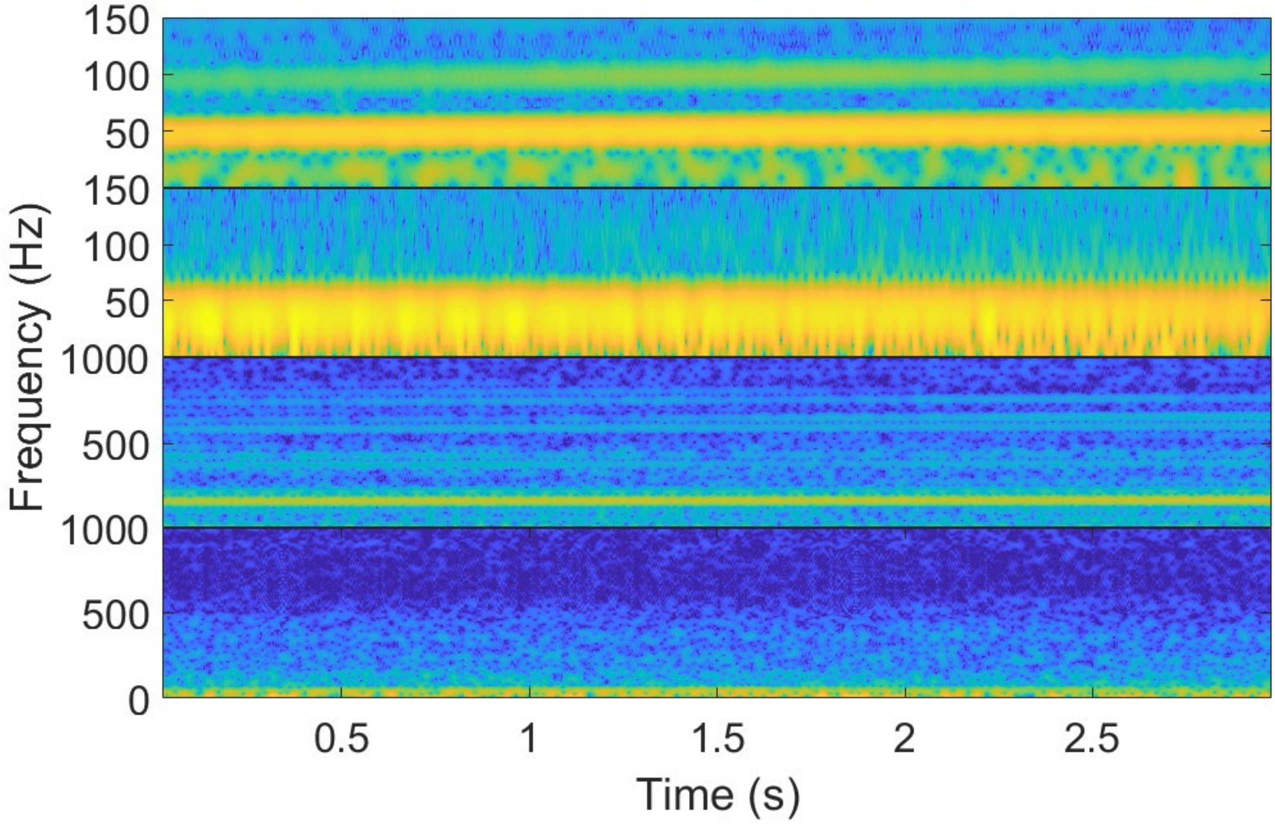

Figure 2: Spectrograms of the recorded introduction sounds for the sensations humming (first row), rumbling (second row), booming (third row) and a sound, which did not elicit any of the three sensations (fourth row).

2.2 Experimental procedure

After the listeners completed the introduction phase, the main experiment started. Before the first run of each sensation, the listeners listened to all sounds of the experiment one after another to become familiar with the dynamic range of the sensation. Afterwards, each sound was played individually in a random order. The task was to rate the respective sensation of each sound on a 9-point Likert scale (see Figure 3). The study was carried out in German, so that both the originally used German terms and the English translations are provided. As an example, for the sensation humming ("Brummen"), the extreme value 1 was labelled with "nicht brummend" ("not humming") and the extreme value 9 with "extrem brummend" ("extremely humming"). For further orientation, the scale ticks 3, 5 and 7 were labelled with "wenig brummend" ("little humming"), "mittel brummend" ("medium humming") and "deutlich brummend" ("clearly humming"). The scale ticks were adapted from the method of categorical loudness scaling [5]. In contrast to the introduction phase, the listeners were not allowed to listen to the sounds repeatedly. For the other two sensations rumbling and booming, the terms "wummernd" and "dröhnend" were used instead of "brummend". Each listener rated all sensations for all sounds three times. The results of the three runs per sensation were averaged and the overall mean values and the interindividual standard errors were calculated.

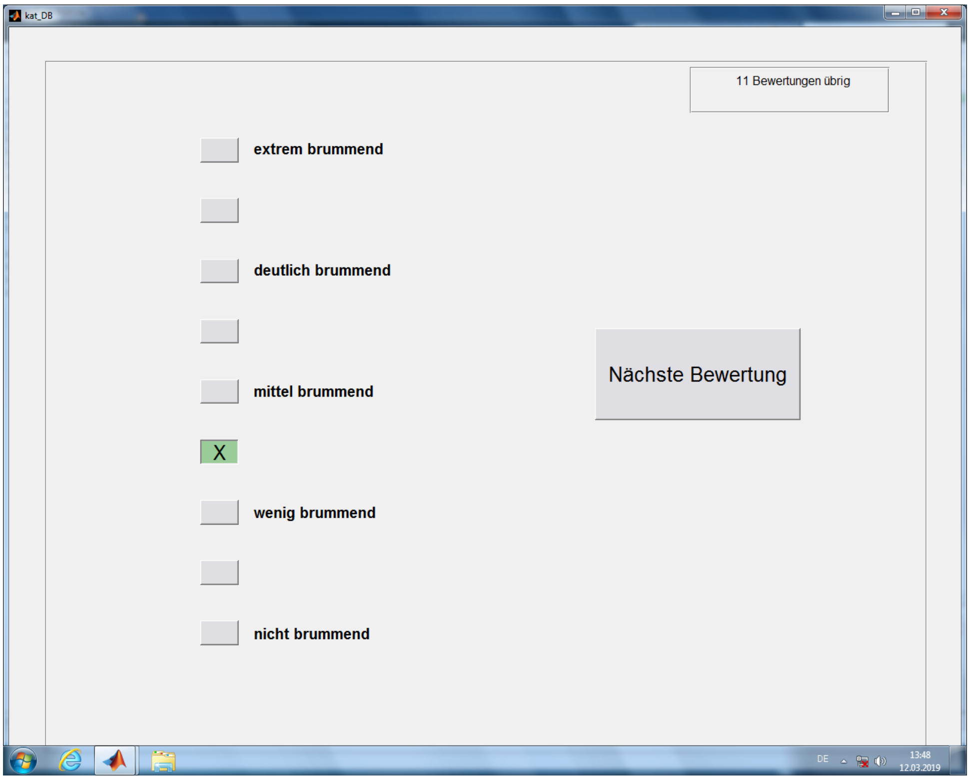

Figure 3: User interface for the categorical rating of the sensation humming (“Brummen”).

2.3 Apparatus

The listeners were seated in a sound-attenuating booth. The stimuli were converted from digital to analog signals using the sound card RME Fireface UC and presented binaurally via Sennheiser HD 650 headphones. The listeners rated each sensation using a touchscreen in front of them.

2.4 Stimuli

Table 1: Variations of the five original sounds of the experiment. The first column shows the sound number of the respective original sound. The second column shows the altered frequency bands. The third column shows the level variation steps of the frequency bands shown in the second column.

Sound number	Frequency bands	Level variations
19	30-42 Hz (1. C.)	-20 dB
	28-34 Hz & 40-46 Hz (SB)	-20 dB
42	35-45 Hz (1. C.)	+5 dB, +10 dB
49	36-44 Hz (1. C.)	-20 dB, -5 dB
63	34-42 Hz (1. C.)	-5 dB
	72-80 Hz (2. C.)	-5 dB
69	30-40 Hz (1. C.)	+5 dB, +10 dB, +15 dB
	30-40 Hz & 68-74 Hz (1. & 2. C.)	+5 dB, +10 dB, +15 dB

For the study, five original sounds were used, which were binaurally recorded at the driver’s seat during slow run-up driving conditions, which are labelled as *Original*. From these original sounds, spectro-temporal variations were adapted by manipulating the level of certain sound components using the Sound Engineering

Tool of the HEAD Acoustics ArtemiS Suite 9.0. The variations were subcategorized into variations of the side bands of a low-frequency component (*SB*), variations of a low-frequency component itself (*1. C.*), variations of a low-frequency component, whose frequency is higher than the one of the first component (*2. C.*) and variations of both the first and second component (*1. C. & 2. C.*). The component levels were either decreased by 5 or 20 dB or increased by 5, 10 or 15 dB. The adjustment steps were selected in a way that the resulting variations sounded considerably different from each other and that the sound pressure levels did not exceed the maximum level according to the vote of the ethical committee. In total, ten variations (see Table 1) of the sounds were created in addition to the five original sounds, so that in total, 15 stimuli were evaluated in the experiment.

2.5 Listeners

Fourteen normal-hearing listeners participated in the experiment. None of them had any hearing difficulties and their audiometric thresholds were 20 dB HL or below for the standard audiometric frequencies between 125 and 8000 Hz.

3 Results and Discussion

Figure 4 shows the mean values and standard errors for the three sensations rumbling, humming and booming. Mean rumbling values range from 2.4 to 7.1, mean humming values from 2.4 to 6.7 and mean booming values from 2.3 to 7.4.

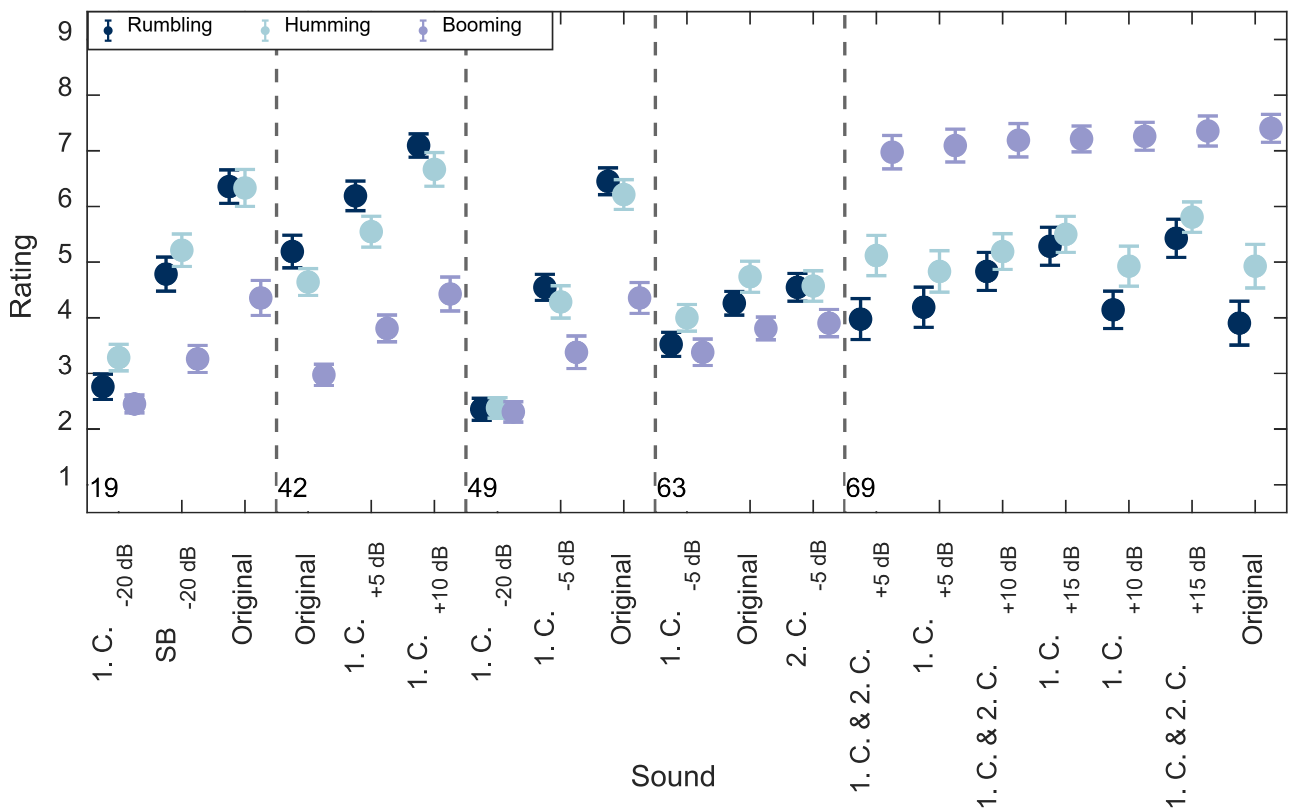

Figure 4: Mean values and interindividual standard errors for the three sensations rumbling (dark blue), humming (light blue) and booming (purple). The numbers in the bottom-left corner of each subpanel refer to the original sounds of Table 1. The labels of the abscissa indicate the respective variation of each sound. The ordinate shows the magnitude of the three sensations, ranging from 1 to 9.

For sound 19, the attenuation of the first sound component by 20 dB resulted in a stronger decrease of the sensations rumbling and humming than the attenuation of the side bands. The influence of on the perceived booming is even smaller, presumably because only low-frequency components were altered. Similar observation can be made for the results of sounds 42 and 49. For sound 42, the level increase of the first component results in a slightly stronger increase of the sensations rumbling and humming than of the sensation booming. This difference is more pronounced for sound 49. While the *Original* sound elicited relatively strong rumbling (6.5) and humming (6.2) sensations, the perceived booming was lower (4.4). A level reduction of the first component by 20 dB resulted in nearly equal values for the three sensations. The variations of sound 63 and sound 69 only revealed small differences for the three sensations. While for sound 63, the small changes could be explained by the relatively small changes of only 5 dB for both the first and the second component, it does not explain the results of sound 69. For sound 69, the increases of the first, the second and both components by up to 15 dB resulted in only relatively small changes in the perceived rumbling and humming. For the *Original* sound all its variations, the booming was similar and much higher than for the other two sensations. This indicates that the sensation of booming dominates the sensations of humming and rumbling for this sound. The listeners hardly seem to notice the changes in the low frequency range when rating the sensation. The more or less constant high booming magnitude is presumably a result from the medium-frequency components which are the same for all these sounds.

When analyzing the interdependencies between the sensations, the rank correlation coefficient according to Kendall [6] of 0.66 reveals that the sensations rumbling and humming were correlated. This correlation may be explained on the basis of the common spectral characteristics that elicit these sensations. Both sensations have in common that they solely depend on the appearance of low-frequency components. However, this study indicates that a strong booming sensation could result in only small changes in humming and rumbling when altering the relevant frequency bands. The rank correlation coefficient of 0.41 between the sensations humming and booming was slightly smaller. The correlation may be explained by the common contribution of an unmodulated low-frequency component to these sensations. However, booming further depends on the appearance of higher-frequency components, which were not altered in this study, hence the smaller correlation than for rumbling and humming. The results for sound 69 and its variations indicate that for prominent higher frequency components, changes of the low-frequency component have a negligible effect on booming. With a value of 0.17, the rank correlation between the sensations rumbling and booming is the lowest correlation between the sensations. This low correlation may be explained by differences in the key features of the sound for the two sensations. Even though rumbling and humming involve low-frequency components and audible modulations, not only the components that are modulated differ but also the modulation frequencies of the sounds eliciting a strong booming are commonly higher than those eliciting a strong rumbling [1].

4 Conclusions

The study shows, that the sensations humming, rumbling and booming are partially correlated, presumably due to common signal properties. All the three sensations depend on low-frequency components, while rumbling additionally involves amplitude modulations and booming is an interaction of a low-frequency component and higher frequency components. The study revealed a certain dominance effect of booming over the two other sensation when booming is large. Even though the terms humming, rumbling and booming are often used interchangeably in the literature, listeners can distinguish them when they are clearly defined prior to the experiment. The sensations should be clearly distinguished, because the sensory impressions and the impact on the pleasantness are considerably different. Overall, a clear definition of the sensations may help to better characterize sound perception and to conduct the appropriate countermeasures to improve sound quality.

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