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ON THE ROLE OF AN INTRODUCTION PHASE IN EXPERIMENTS ON THE PERCEPTION OF VEHICLE INTERIOR NOISE

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ABSTRACT

A possibility to characterize auditory perception of vehicle interior sounds is to ask the listener to rate the sound with respect to a specific sensation. Some sensations are familiar to all listeners, e.g., loudness as the psychoacoustic correlate of the physical property intensity. Other sensations either are not familiar to the non-expert listeners or may have different meanings to the listeners. The latter category includes the sensations of humming, rumbling and booming which are commonly associated with sounds that contain low-frequency tonal components. In the context of vehicle interior sounds, these were the topic of Doleschal et al. [1]. They familiarized the non-expert listeners to the sensations through an introduction phase where three sounds were presented to the listeners: an artificial prototypical sound that contained key features for the specific sensation, a recorded vehicle interior sound where the magnitude of the sensation was high and a third vehicle interior sound that did not elicit any of the three sensations. The present study investigates the benefit of such an introduction phase by comparing the results of non-expert listeners without an introduction phase to those with an introduction phase.

Keywords: *auditory sensation, vehicle interior noise, non-expert listeners, prototypical sounds.*

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1. INTRODUCTION

The perceived quality of a product depends, among others, on the sound that the product emits. Several perceptual aspects of the sound influence the sound quality. A possibility to characterize these perceptual aspects is to determine the magnitude of auditory sensations. Car manufacturers increasingly consider these auditory sensations to evaluate the perception of the sound quality [2]. Usually, sound quality is determined by more than one sensation (e.g., [3]). Thus, a combination of auditory sensations can be used to predict sound quality (e.g., [4]). The set of sensations, which has to be considered for the assessment of sound quality, depends on the type of product sound. The magnitude of the sensations is often predicted using calculation tools. Some of the calculation tools of sensations, such as loudness or sharpness, are standardized (e.g., [5], [6]). For other less common sensations, it may be necessary to quantify their magnitude in listening experiments.

The present study focusses on the perception of vehicle interior noises in vehicles with a combustion engine running at low speeds. A common effect of this downspeeding is that the engine emits low-frequency tonal components. These can have a negative impact on the perceived sound quality, since audible low-frequency tonal components are often described as being unpleasant, tiring and stressful [7].

Humming, rumbling and booming are sensations that are specific to the perception of such low-frequency tonal components. A problem with these sensations is that they are not well defined, even in the scientific literature, and are sometimes used interchangeably (see, e.g. [1], for an overview).

Definitions that allow differentiating between the three sensations are provided in [7]. According to [7], the sensation of rumbling is caused by a single component or multiple components in a frequency range below 100 Hz with audible temporal amplitude modulations at low rates. If the audible low-frequency component is not modulated in amplitude over time, it elicits the sensation of humming. If a sound contains such an unmodulated low-frequency component and, in addition, higher-frequency components which are modulated at a rate that is similar to the frequency of the low-frequency component, the sound elicits the sensation of booming.

Doleschal et al. [1] used the definition of [7] to measure the impact of variations of parameters of interior noises of vehicles with a combustion engine running at low speeds on the magnitude of these sensations. Their listeners were non-experts. Hence, the experiment started with an introduction phase, where the meaning of the three sensations were explained by presenting sounds. The details of the introduction phase are provided in the following section 2.

The aim of the present study is to investigate the effect of such an introduction phase on the results. To this end, results of an experiment on humming, rumbling and booming of recorded sounds without an introduction phase were compared to an experiment, where the same recorded sounds were rated with a preceding introduction phase.

2. METHODS

The present study is a following-up study of a joint project of the Acoustics group (head Prof. Steven van de Par) of the Carl von Ossietzky University Oldenburg and the Department of Experimental Audiology (head Prof. Jesko L. Verhey) of the Otto von Guericke University of Magdeburg (FVV project no. 1304, see [8]). In that project, a set of 12 recorded sounds from the vehicle interior were chosen for each sensation under the constraint that, for each sensation, a large dynamic range is covered by the set of sounds and that there is some overlap between the sets for the different sensations. As a basis, the ratings of an expert group of fourteen normal-hearing listeners (eleven male, three female, age between 23 and 40 years) of thirty recorded sounds per sensation were used. There was an overlap of ten sounds, i.e. these ten sounds were rated with respect to all three sensations. The twelve sounds per sensation of the main experiment were a subset of the 30 sounds that were rated by the expert listeners. The sounds were recorded during real driving situations on a test track using a binaural headset at the drivers' left and right ear position. All expert listeners were members of either the Carl von Ossietzky University of Oldenburg or the Otto von Guericke University of Magdeburg.

In the main experiment of the FVV project, 40 listeners (18 male, 22 female), all non-experts in vehicle acoustics, were asked to rate the sounds on a nine-point Likert scale, ranging from one to nine. For humming, the scale ticks 1, 3, 5, 7 and 9 were labelled with "nicht brummend" ("not humming"), "wenig brummend" ("little humming"), "mittel brummend" ("medium humming"), "deutlich brummend" ("clearly humming") and "extrem brummend" ("extremely humming"). Corresponding tick labels were used for the other two sensations, i.e., for booming "brummend" is replaced with "dröhnend" (booming in German) and for rumbling it is replaced with "wummernd" (rumbling in German). The rating was repeated three times for each sound. The mean of these three ratings was taken as the final individual estimate of the magnitude of the sensation for the sound.

At the beginning of the main experiment of the FVV project, the sensations were explained in an introduction phase by presenting three sounds to the listeners. The first was an artificial prototypical sound that contained key features for the specific sensation. The prototypical sounds are provided on the website of the Department of Experimental Audiology of the Otto von Guericke University Magdeburg [9]. Their spectra are schematically shown in Figure 1.

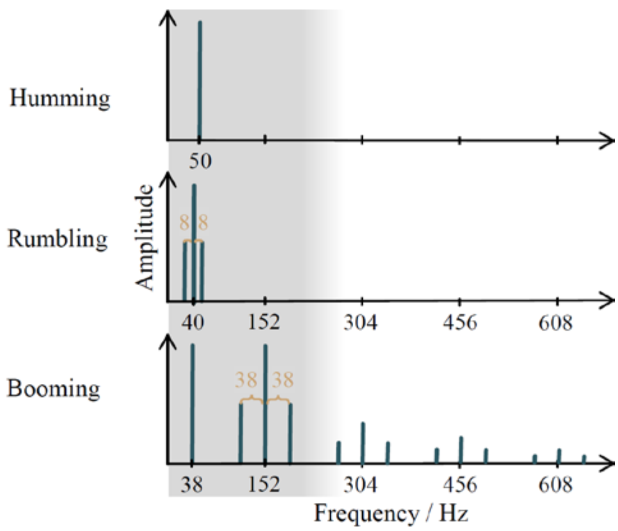

Figure 1. Schematic spectra of the prototypical sounds for the three sensations.

For rumbling and booming, modulated sounds are used. The modulation produces sidebands, one below and one above the component at a spectral distance that is equal to the modulation frequency (8 Hz for rumbling, 38 Hz for

booming). The other two sounds of the introduction phase were real recordings, one, where the magnitude of the sensation was high and one that did not elicit any of the three sensations. Details of the sounds are provided in [1].
The experiment of the present study without the introduction phase was essentially a replication of the main experiment of the FVV project, except for the introduction phase, which was replaced by a questionnaire, where the listeners were asked to explain the sensations and provide examples of sounds they associated with the sensations.
Twenty-one listeners (eleven male, ten female, age between 18 and 36 years) participated in the experiment. All of them were normal hearing, i.e., their thresholds were lower than 20 dB hearing level at the standard audiometric frequencies. Listeners were seated in a double-walled sound-attenuating booth. The stimuli were converted from digital to analog signals with the sound card RME Fireface UC and presented binaurally via Sennheiser HD 650 headphones. According to the manufacturer, these headphones are diffuse-field equalized. The headphones were calibrated using an artificial ear (Brüel & Kjaer type 4153, Nærum, Denmark). During the experiment, the listeners rated the sound with the categorical scale described above. This scale was presented on a touchscreen in front of the listener. The setup was the same as used in the main experiment of the FFV project, i.e., the corresponding experiment with introduction phase.

3. RESULTS AND DISCUSSION

3.1 Descriptions of the non-expert listeners

The question time in the experiment without introduction phase revealed that not all non-expert listeners knew the meaning of the sensations or had a different definition of the sensations. Table 1 shows the number of listeners, who described the sensation more or less in agreement with the definition of [7].
Eight listeners described a humming sound as a sound containing "constant" low-frequency tonal components (i.e. in agreement with the definition of [7]). Others were less exact in their description, i.e., humming was described as a low-frequency noise. In total, 14 of the 21 listeners provided descriptions that were more or less in agreement with the definition of [7]. Rumbling was more difficult for the non-expert listeners. In total, seven descriptions were classified as being consistent with the definition of the perception of a slowly varying low-level tonal component. A common association with rumbling was a bassy music (in a club).

The majority of the listeners had difficulties with the sensation booming. Only four listeners described booming as the perception of a sound containing low and high components. The others had own definitions. In that group, the sensation booming was often associated with loud or annoying sounds.

Table 1. Percentage of the description of the non-expert listeners that agree with the definition of [7] (here labelled as "correct" descriptions).

Sensation	Percentage of "correct" descriptions
Humming	67 %
Rumbling	33 %
Booming	19 %

3.2 Results of non-expert listeners with and without introduction phase

Figure 2 shows average ratings on the categorical scale of all listeners for humming. The results of the experiments without introduction phase are shown with light blue symbols, those of the experiment with an introduction phase with grey symbols.

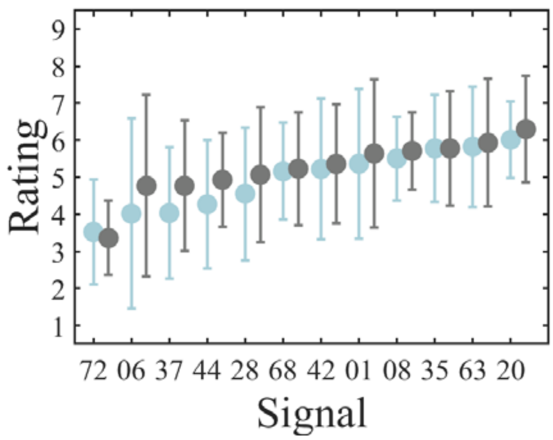

Figure 2. Average ratings and inter-individual standard deviations for humming. Results of the experiment without introduction phase are shown in color, those with introduction phase in grey.

For a better visibility, the data points of the experiment without introduction phase are slightly shifted horizontally to the left and those of the experiment with introduction phase to the right. Error bars indicate plus/minus one inter-individual standard deviation of the mean.

The results for the twelve sounds are shown in ascending order from left to right for the experiment with an introduction phase. With the twelve selected sounds, the humming ratings ranged from slightly above 3 (little humming) to 6 (between medium humming and clearly humming). The dynamic range for the humming ratings without introduction phase was about the same as that of the ratings of the experiment with an introduction phase. For all sounds, the difference between the results with and without introduction phase was less than 1. The correlation of the two data sets was very high (r= 0.93). There is a tendency of a slightly higher inter-individual standard deviation (on average 3 percent higher) for the results of the experiment without an introduction.

Figure 3 shows the results for rumbling. Average results of all listeners and inter-individual standard deviations are shown of the experiment without an introduction phase (dark blue) and of the experiment with an introduction phase (grey). The dynamic range (slightly above 3 up to 7) of the results for rumbling with introduction phase was slightly higher than that for humming.

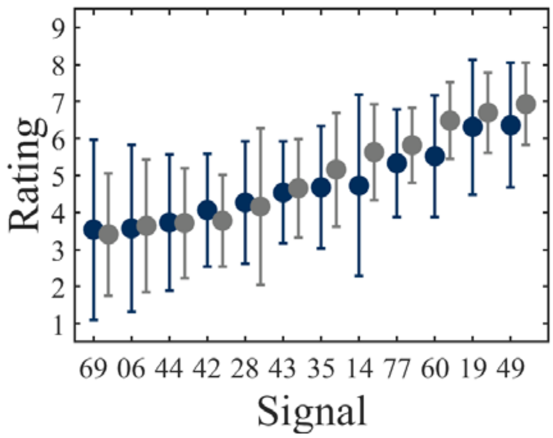

Figure 3. The same as Figure 2, but now for rumbling.

The average ratings for rumbling of the experiment without introduction phase differed by not more than 1 on the nine-point scale from the corresponding results of the experiment with an introduction phase. The correlation of the results of the two experiment was very high (r=0.97). The inter-individual standard deviations of the results without an introduction phase were, on average across the results for all sounds, about 30% higher than for the corresponding results of the experiment with an introduction phase. Thus, the individual results vary across listeners considerably more without an introduction phase than with an introduction phase. This may be due to unfamiliarity of the sensation to the non-expert listeners. In agreement with this hypothesis, the analysis in section 3.1 revealed that only seven of the 21 listeners described the sensation rumbling consistent with the definition of rumbling of [7]. Note that this definition was used as the basis for the prototypical sound in the introduction phase. In contrast, 14 out of 21 listeners explained the sensation humming according to the definition of [7]. This may explain why the inter-individual standard deviations were similar for the experiment on humming with and without an introduction phase.

Figure 4 shows the results for booming of the experiments without (in purple) and with (in grey) an introduction phase. Apart from a different color for the results of the experiment without an introduction phase, the data representation is the same as in the previous figures.

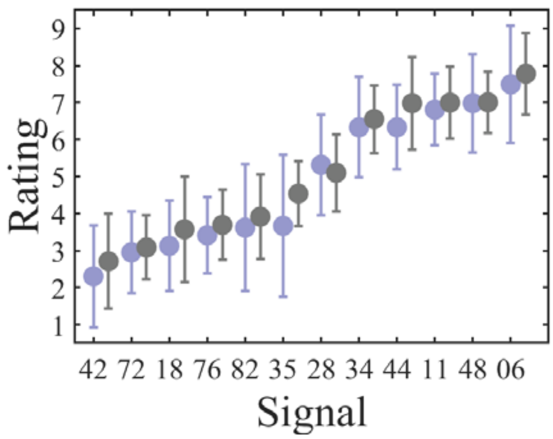

Figure 4. The same as Figure 2, but now for booming.

The dynamic range (slightly below 3 up to about 8) of the results for booming with an introduction phase was higher than for the other two sensations. The average ratings for booming of the experiment without an introduction phase differed by less than 1 on the nine-point scale from the corresponding results of the experiment with an introduction phase. The correlation of the results of the two experiments was, as for rumbling, very high (r=0.97). The inter-individual standard deviation of the results without introduction were, on average across the results for all sounds, about 28% higher than for the results of the experiment on booming with an introduction phase. As for rumbling, this is presumably due to difficulties in understanding the sensation without an introduction phase. Only seven of the 21 listeners explained the sensation according to the definition of [7] that was used in the present study and which was used as a basis of the generation of the prototypical sound (see section 3.1).

3.3 Comparison to results of expert listeners

The previous section 3.2 showed a high correlation between the results of the experiments without an instruction phase to those with an instruction phase, as described in the Methods section. In this section, it is investigated to what extent the results of the non-expert listeners agree with the ratings of expert listeners. In the experiment with expert listeners, an eleven-point Likert scale was used, where the top and bottom end were labelled: For humming, these were "nicht brummend" (not humming) at the bottom and "brummend" (humming) at the top of the scale. The labels for the other two sensations were similar; only the German term for humming was replaced with "wummernd" for rumbling and "dröhnend" for booming. For comparison, the eleven-point scale was remapped to the nine-point scale that was used for the non-expert listeners. In addition to the different scale, the expert listeners rated a larger set of sounds than the non-expert listeners (30 sounds instead of 12).

In Figure 5, the ratings of booming of the experts are drawn over the ratings of the non-expert listeners in the experiment without an introduction phase. The (red) dashed line indicates the diagonal. The data points are very close to this diagonal, indicating that the rescaled ratings of the expert listeners were similar to the ratings of the non-expert listeners. The correlation between the two data sets was high (r = 0.95).

Figure 6 shows the comparison of the data of expert and non-expert listeners for rumbling. The data representation is the same as in Figure 5, except for the color of the circles (now dark blue). The dynamic range of the ratings of the expert listeners was slightly larger than that of the ratings of the non-expert listeners. There is a tendency that the non-expert listeners rated sounds with a low magnitude of rumbling as slightly more rumbling than the expert listeners. The correlation was again high (r = 0.90).

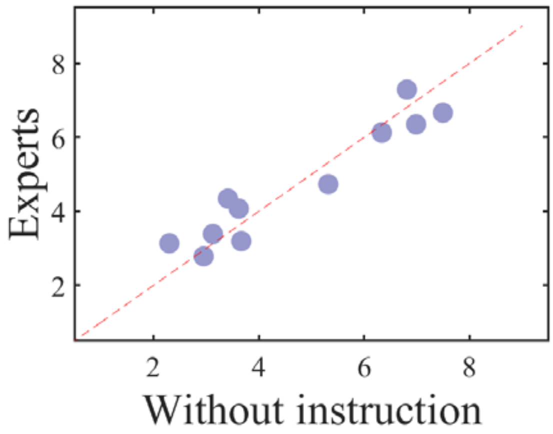

Figure 5. Comparison of the results for booming of the non-expert listeners in the experiment without introduction phase and those of the expert listeners.

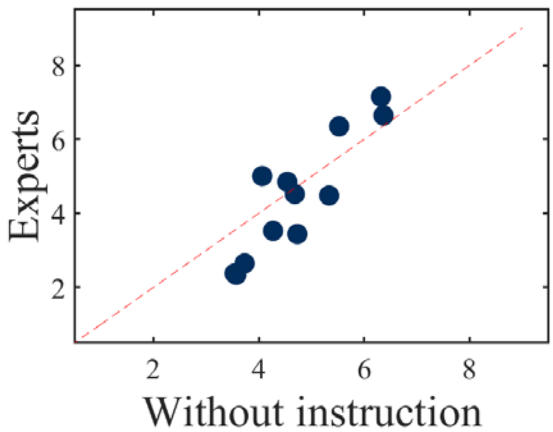

Figure 6. The same as Figure 5, but now for rumbling.

Figure 7 shows the comparison of the ratings for humming for the two groups of listeners. As for the other two sensations, the data points are close to the diagonal and the correlation of the results of the expert and the non-expert listeners was high (r=0.86).

Overall, the comparison indicates that, on average over all listeners, they were similar in their ratings of the sensations humming, rumbling and booming.

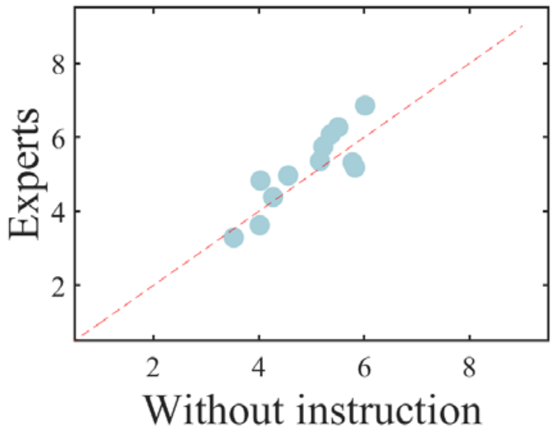

Figure 7. The same as Figure 5, but now for humming

4. SUMMARY AND CONCLUSION

The present study compared the results of experiments on humming, rumbling, and booming with an introduction phase with those of an experiment without an introduction phase. There was no overlap in the set of listeners of these two experiments. The correlation of the results of the two data sets was high for all three sensations, indicating that the average results were hardly affected by the introduction phase. The main difference was that the inter-individual standard deviations were considerably higher for the sensations booming and rumbling. These were the sensations, which were less familiar to the non-expert listeners. The higher standard deviation has an impact on the accuracy of the estimation of an average magnitude of a sensation, given that this accuracy is determined by the standard error (standard deviation divided by the square root of the number of listeners). The present data indicate that, for the same accuracy, up to 40% less listeners are required, when the experiment is preceded by an introduction phase. This large benefit of an introduction phase is only likely to be observed for sensations, which are unfamiliar to the listeners. The data for humming supports this hypothesis: Most non-expert listeners were familiar with humming and the inter-individual standard deviations were similar for the experiments with and without an introduction phase.

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