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HUMMING AND RUMBLING: EXPERIMENTS AND MODEL PREDICTIONS

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ABSTRACT

The sensations humming and rumbling are commonly associated with low-frequency pure tones (humming) and low-frequency amplitude modulated tones (rumbling). It was investigated how the magnitudes of these sensations depend on the following signal parameters: carrier frequency, modulation frequency, modulation depth, and sound pressure level (SPL). Participants rated all signals on a categorical scale for each sensation. For a subset of these sounds, participants were also asked to make pairwise comparisons of the magnitude of the elicited sensations. The answers to the pairwise comparison task were evaluated using the Bradley–Terry model, transforming them to values on a ratio scale. These were then compared to the categorical ratings. In general, the magnitude of humming decreased as the carrier frequency increased, was lower for high modulation depth and higher for high SPL. Rumbling was strongest for low carrier frequencies modulated with a high modulation depth and high SPL. Remarkably, rumbling was also found for unmodulated tones with very low frequency. In addition to the experiments, a model predicting the two sensations was developed and evaluated using the experimental data. The model structure was based on established filter-bank models of auditory spectral selectivity and modulation detection in human hearing.

Keywords: *Psychoacoustics, Sensations, Low-Frequency, Amplitude modulation, Modelling*

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1. INTRODUCTION

Low-frequency tonal sound is emitted by technical devices like e.g. vehicles and heat pumps. Humming and rumbling are sensations associated with those sounds and have been used e.g. to characterise vehicle interior sounds [1]. In this study, artificial sounds were used in order to investigate the dependence of humming and rumbling on basic signal parameters.

2. METHODS

Sound was presented via Sennheiser HDA 280 headphones monaurally. In Experiments 1 and 2, subjects were asked to rate their sensation for each sound on a scale ranging from the German language equivalents of 'not humming', over 'little humming', 'medium humming', and 'clearly humming' to 'extremely humming' as well as unnamed categories in between each of the named categories (analogous for rumbling). Pure tones and amplitude-modulated (AM) tones were used as signals. In Experiment 3, a subset of sounds from Experiment 1 was used in a complete pairwise comparison experiment. 8 normal hearing subjects with absolute thresholds < 15 dB across all audiometric frequencies below 2 kHz took part in Experiments 1 and 2. A subset of 6 subjects also took part in Experiment 3.

2.1 Experiment 1

In Experiment 1, the effect of carrier frequency, modulation rate, and modulation depth were investigated for sound pressure levels according to a loudness level of 50 phon [2] for the respective carrier frequencies. Parameters were every combination of the carrier frequencies 20,

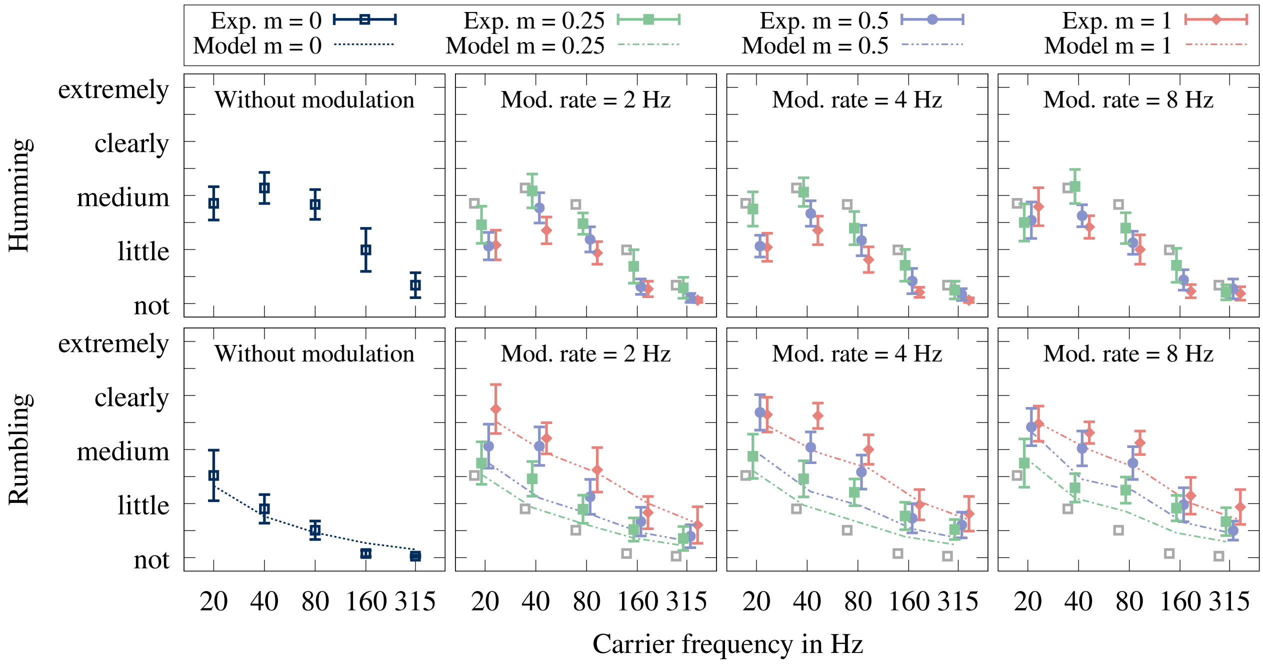

Figure 1. Experimental data for humming (top row) and rumbling (bottom row) from Experiment 1 shown as markers, errorbars indicate plus and minus one standard error of the mean. In the six panels for modulated sounds, the experimental results for unmodulated sounds from the leftmost panel are repeated as grey markers for reference. Some marker groups have a slight horizontal offset for better readability. Model predictions for the same paradigm are indicated by lines, using the same offset.

40, 80, 160, and 315 Hz, the modulation rates 2, 4, and 8 Hz, and the modulation depths 0, 0.25, 0.5, and 1.

2.2 Experiment 2

In Experiment 2, the effect of carrier frequency, modulation rate, and loudness level was investigated for unmodulated (modulation depth $m = 0$) and fully modulated ($m = 1$) sounds. Parameters were every combination of the carrier frequencies 20, 40, 80, 160, and 315 Hz, the modulation rates 2, 4, and 8 Hz, and sound pressure levels according to the loudness levels 30, 40, and 50 phon [2] for the respective carrier frequencies.

2.3 Experiment 3

Eleven sounds from the set of Experiment 1 were used. Subjects were presented with each possible pair combination and asked to pick the one that elicited the stronger sensation of humming or rumbling, respectively. For each sound, the score on a ratio scale was calculated using the Bradley-Terry model [3]. These scores were then compared to numerical representations of the named categories ranging from 1 for 'not humming' to 9 for 'extremely humming' (analogous for rumbling). The correlation between the results of both experiments was used for validation.

3. MODEL STRUCTURE

The model for predicting rumbling was based on the filterbank model by [4], used originally to predict masked thresholds of modulated sounds, among other things. A publicly available version of this model was used [6]. The model's input filter stage was modified by adding a first-order high-pass filter with a cutoff frequency of 140 Hz to account for the slope of absolute hearing thresholds in the low-frequency range, which was not represented enough by the original filter. Peripheral filters with characteristic frequencies of 63, 125, and 250 Hz were used. The modulation filters used in the present model were

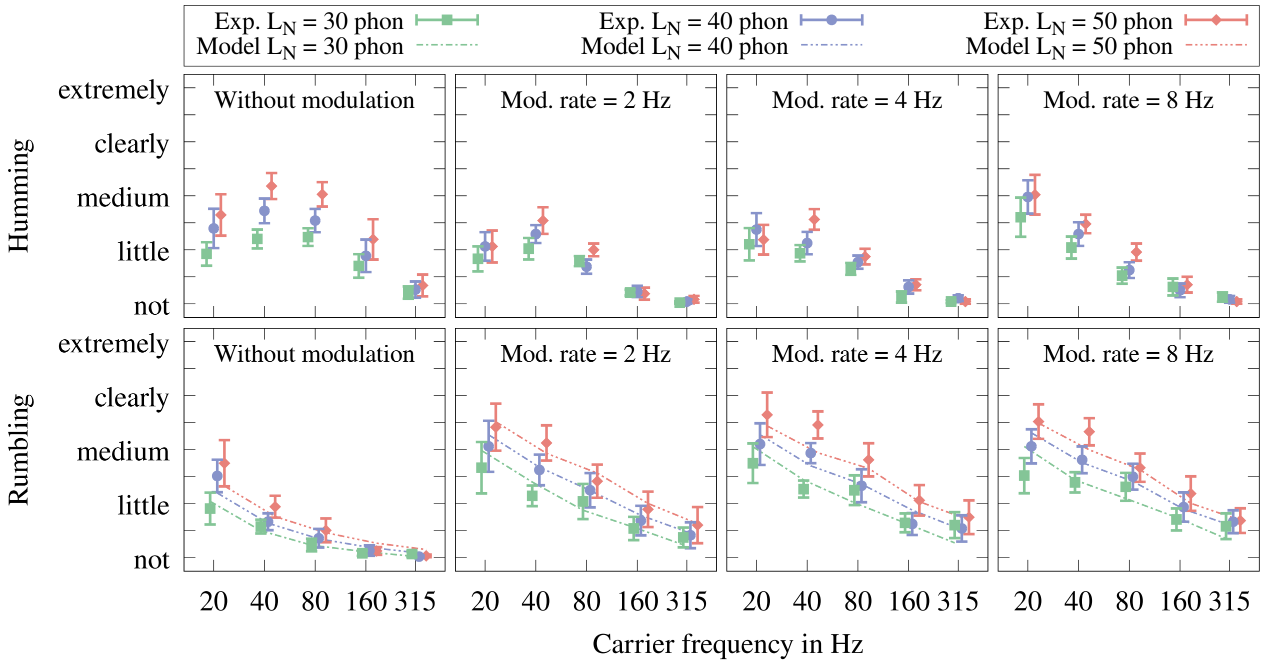

Figure 2. Experimental data for humming (top row) and rumbling (bottom row) from Experiment 2 shown with the same representation as in Fig. 1.

a lowpass filter with a cutoff frequency of 2.5 Hz and three bandpass filters with center frequencies of 5, 10, and 15 Hz, respectively. From each modulation filter, the maximum steady state excitation $E_{i,j}$ (indices referring to peripheral filter number i and modulation filter number j, respectively) was computed. A rumbling score was then computed as a linear combination of modulation filter excitations $R = \boldsymbol{p}^\top \boldsymbol{E}\boldsymbol{m} = \sum_{i,j} p_i \cdot E_{i,j} \cdot m_j$ with weighting coefficients of the peripheral filters $\boldsymbol{p}$ ($(1.178, 0.356, 1.193) \cdot\ 10^{-4}$) and weighting coefficients for the modulation filters $\boldsymbol{m}$ (45.20, 3.76, 63.10, 0.01), which were both fitted to the data of Experiment 2 using the least squares method.

4. EXPERIMENTAL RESULTS

4.1 Experiment 1

Results of the categorical ratings in Experiment 1 are shown in Fig. 1. The strongest humming was found for carrier frequencies 40 Hz and 80 Hz. In most conditions, humming decreased with modulation depth. Nearly no humming was found for the carrier frequency 315 Hz. Rumbling was found for pure tones with a frequency of 80 Hz and lower. For most conditions, it increased with modulation depth.

4.2 Experiment 2

Results of the categorical ratings in Experiment 2 are shown in Fig. 2. For pure tones, the strongest humming was found for the frequencies 40 and 80 Hz, increasing with loudness level. In most conditions, humming decreased for amplitude-modulated tones. However, for a modulation rate of 8 Hz, humming increased with modulation for the lowest carrier frequency of 20 Hz. This effect was also found in Experiment 1 for the highest modulation depth. In conditions that elicited rumbling, it increased with loudness level. Rumbling also increased with modulation, similar to Experiment 1.

4.3 Experiment 3

The results of Experiment 3 are shown in Fig. 3. Parameters of the Bradley-Terry model were calculated from the subjects' pairwise comparison results. The logarithm of these parameters was calculated and linearly transformed (drawn on the ordinate), to compare them to the results

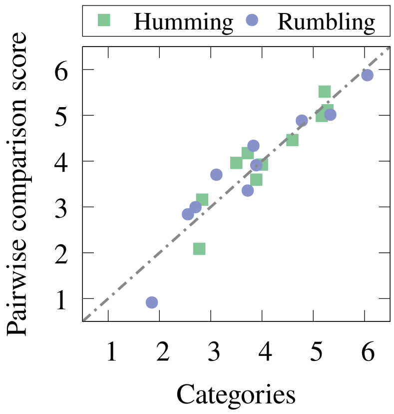

Figure 3. Comparison of scores from the pairwise comparison in Experiment 3 to a numerical representation of the categorical results from Experiment 1.

from Experiment 1 (drawn on the abscissa). The pairwise comparison score in Experiment 3 correlated well with the categorical ratings in Experiment 1, the correlation coefficients were 0.929 for humming and 0.943 for rumbling.

5. MODEL PREDICTIONS

Model predictions are shown in Fig. 2 together with the experimental results for Experiment 2. They are drawn as lines in the respective panels. The model predicted an increase of rumbling with loudness level and an increase of rumbling with modulation, in agreement with the experimental data. Mostly, the model predictions are within the standard error margins of the measurements. However, the effect of loudness level on rumbling is smaller in the predictions, when compared to the experimental data. Additionally, model predictions for Experiment 1 are shown in Fig. 1 Note that the model was fitted only to the data from Experiment 2. The model predicted an increase of rumbling with modulation depth, in agreement with the experimental data. However, the model was less sensitive for small modulation depths like 0.25 and 0.5, when compared to the experimental data.

6. DISCUSSION

The maximum values of the average ratings were between the category 'medium' and 'clearly', even for the highest loudness levels used in the experiment. However, the maximum loudness level was 50 phon. In comparison, a 1 kHz tone with a loudness level of 50 phon has an average loudness on a categorical scale between soft and medium loud [7].

The increase in humming for modulated tones with a carrier frequency of 20 Hz and a modulation rate of 8 Hz in comparison to unmodulated tones could possibly be explained by a secondary effect of loudness. When modulations are introduced, the higher sidetones occupy higher equal-loudness level contours than the carrier tones, due to the high slope of equal-loudness level contours for low frequencies. The higher humming rating in these conditions might therefore be a consequence of higher loudness.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] F. Doleschal and J. L. Verhey, "Modeling the perceptions of rumbling, humming and booming in the context of vehicle interior sounds," *Applied Acoustics*, vol. 210, p. 109441, 2023.

[2] "Acoustics — Normal equal-loudness-level contours," standard, International Organization for Standardization, Geneva, CH, 2023.

[3] R. A. Bradley and M. E. Terry, "Rank analysis of incomplete block designs: I. the method of paired comparisons," *Biometrika*, vol. 39, no. 3/4, pp. 324–345, 1952.

[4] M. L. Jepsen, S. D. Ewert, and T. Dau, "A computational model of human auditory signal processing and perception," *The Journal of the Acoustical Society of America*, vol. 124, no. 1, pp. 422–438, 2008.

[5] R. Meddis, L. P. O'Mard, and E. A. Lopez-Poveda, "A computational algorithm for computing nonlinear auditory frequency selectivity," *The Journal of the Acoustical Society of America*, vol. 109, no. 6, pp. 2852–2861, 2001.

[6] L. C. Paulick, "CASP for AFC," `https://gitlab.com/lpau/casp_forafc`, 2024.

[7] W. Heeren, V. Hohmann, J. E. Appell, and J. L. Verhey, "Relation between loudness in categorical units and loudness in phons and sones," *The Journal of the Acoustical Society of America*, vol. 133, no. 4, pp. EL314–EL319, 2013.