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Tonality Ratings and Unpleasantness Judgements for Synthesized EV Acceleration Sounds Including Gear Orders

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Introduction

Tonal sounds are often a part of the interior sound in electric vehicles (EV) and can also have an effect on the judged sound quality. Depending on the specific driving condition and sound source, tonal components can be relevant in the EV context, both at higher and at lower frequencies [1, 2]. When the level of broadband background noise is low, tonal components are often not sufficiently masked by it. Accordingly, tonal sounds from the drivetrain can be particularly audible in dynamic driving conditions at low speed like acceleration in urban traffic. For stationary sounds containing rather low frequencies up to 400 Hz, tonal components may become detectable with rising tone level but the pleasantness is not automatically reduced [2], whereas at higher frequencies, tonal sounds can be rather unpleasant or annoying [3, 4]. In the present study, the influence of the prominence and composition of tonal components on tonality ratings and unpleasantness judgments was investigated for different simulated electric motor order run-up sounds. The study is part of the AudioOpt project which is aiming at a validation of existing psychoacoustic models predicting the perceived tonality [5] and dissonance perception [6] as well as gaining a better understanding of the relationship between both sensations and unpleasantness judgements in the EV context.

Methods

In laboratory listening experiments, volunteers rated the unpleasantness and the tonality of the sounds in two successive experiments, taking place on different days. Each experiment started with written instructions explaining the experiment. For the tonality task, three sounds consisting of a white noise background and a single embedded tone at fixed frequencies of either 500 Hz, 1 kHz, or 2 kHz, moving up and down in level, were used to introduce and define the concept of tonality similar like in the work of Vormann [7]. Tonality was explained as the loudness of the tonal content (in German: "Lautheit des tonalen Anteils") as suggested by Hansen et al. [8, 9]. It was also explicitly clarified that tonality is independent from pitch height, which should not be considered for the tonality rating. The tonality and the unpleasantness rating task are preceded by an orientation phase with twelve selected sounds, which gave the participants an overview of the dynamic range and richness in sound characteristics covered by the stimulus set. The ratings itself were collected with a 9-point scale in both tasks. The scale was an extension of a 5-point scale with Rohrmann labels with four additional unlabeled in-between categories. In addition to the semantic labels, all categories were also numerically labeled from 0 ("not at all") to 8 ("very") to support the equidistant interpretation of the categories.

Stimuli

A total of 185 run-up sounds were used for the listening tests. The investigated stimulus parameters were derived from an analysis of different measured run-up sounds delivered from industrial partners and a literature review. The identified parameters were often close or similar to those used by Doleschal et al. [10], confirming their relevance and partially allowing for direct comparisons. The signals used here were created by a custom synthesizer [11] simulating a run-up from 250 to 2500 RPM within a duration of 8 seconds. All sounds were based on the same broadband background noise with flat spectral envelope up to 40 Hz and a spectral decay of about 12 dB/oct. above. Very low frequency content below 20 Hz was removed to reduce stressing the headphones. The sound pressure (not SPL) of the broadband background noise signal increased linearly over time and reached 79 dB SPL at the end of the signal. The embedded tonal signatures were linear sweeps of either single or multiple motor orders: 24, 48, 24+48, 24+40+48. For the 24th order, the frequency swept linearly from 100 Hz to 1 kHz and for the 48th order from 200 Hz to 2 kHz. The level of the 24th order was varied threefold to 30 dB, 37 dB, and 44 dB SPL and kept fixed during each run-up condition. The levels of all higher orders were determined from a -6 dB/oct. decay relative to the 24th order, which means that the 48th order was always 6 dB lower in level than the 24th order, whether it was present or not. The lowest tone level (30 dB) was chosen to create tones slightly above the listening threshold. The highest value of the tone level (44 dB) is well above what would reasonably occur inside an EV. These conditions were included to cover the dynamic range towards highly tonal sounds which would not have been comprised by recorded EV interiors sounds alone. Figure 1 shows exemplary spectrograms of the different tonal signatures at the highest tone level of 44 dB SPL. The simulated run-up sounds were either without any simulated gear orders or with one

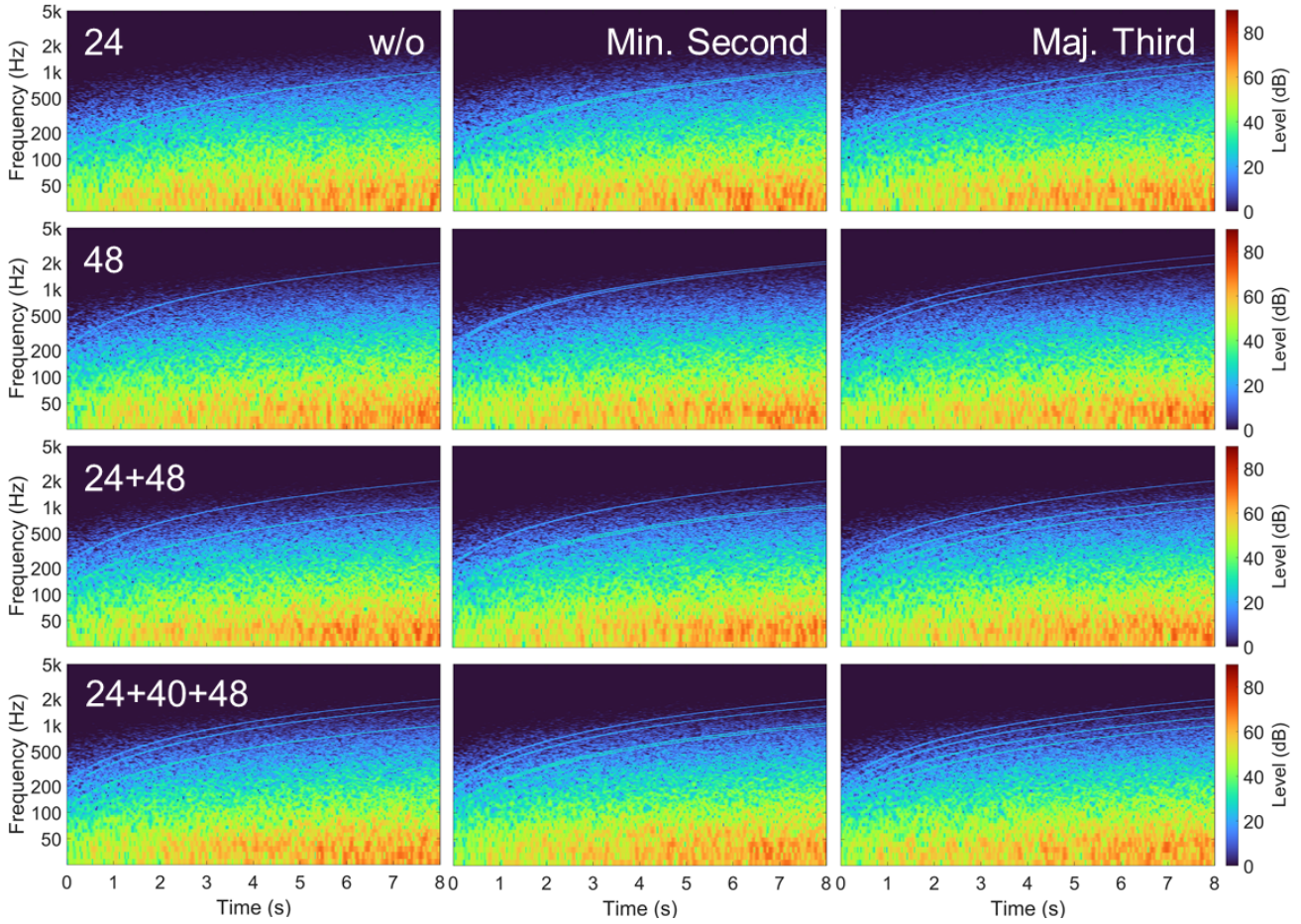

Figure 1: Exemplary spectrograms of the used sounds showing the composition of orders from top to bottom (24, 48, 24+48, 24+40+48) and additional gear tones at different gear ratios from left to right (w/o, Min. Second, Maj. Third) for a medium tone level of 37 dB.

additional gear order, forming either a consonant (Maj. Third, 1:1.26) or dissonant (Min. Second1, 1:1.06) frequency interval with the lowest present motor order. The stimulus set also included conditions without any embedded tones (just the broadband background noise) and conditions with different simulated structural resonances which are presented in another publication [12].

Listening Setup

The listening experiments were carried out in single walled sound attenuating listening booths. The sounds were presented diotically via open headphones (Sennheiser HD650) which were driven by the headphone output of an USB audio interface (RME Fireface UC), connected to a computer. The listening setup was calibrated using an artificial ear (B&K Type 4153) and corresponding measurement amplifier. For the calibration, a stationary sinusoid signal with a defined level was created by the same EV sound synthesizer.

Participants

Overall, 30 volunteers (21 female, 9 male) participated in the listening experiments. Their mean age was 24 years (minimum: 20 years, maximum: 36 years). Roughly one half of the participants already had participated in other listening tests while the other half had no prior experience with listening tests. The Research Ethics Committee of the University of Oldenburg had no objections regarding the study (Drs.EK/2024/019).

Results

Influence of tonal order composition and gear ratios

The mean tonality ratings are shown in Figure 2 and the mean unpleasantness ratings in Figure 3. Unsurprisingly, the tonality and unpleasantness ratings increase with rising tone level, which had a very large effect strength and which was significant between all three levels in both cases. The order composition had a large effect strength for tonality and a medium effect strength for unpleasantness. For tonality, significant differences were found between all of the four different order compositions, whereas the unpleasantness is mostly driven by the highest present component. The gear ratio had a small effect strength and a similar impact on the unpleasantness and tonality ratings. The addition of gear orders leads to a significant difference but between the two different gear ratios no statistically significant difference was found. The interaction between order composition and gear ratio was also significant with a small effect size for the tonality and the unpleasantness rat-

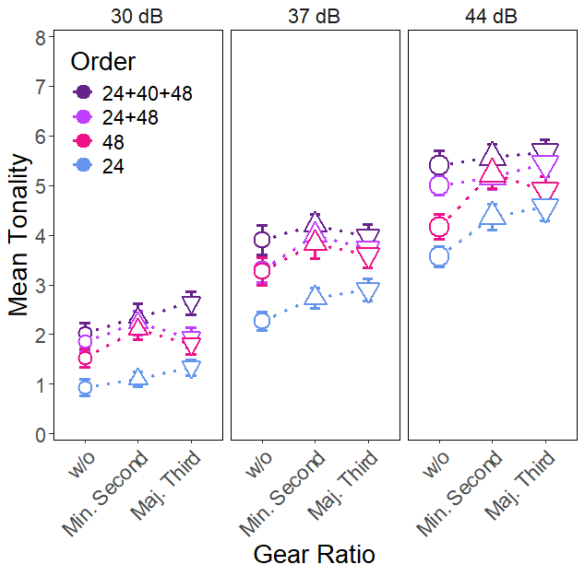

Figure 2: Mean tonality ratings (N=30). Subplots indicate different tone levels. Errorbars show standard errors.

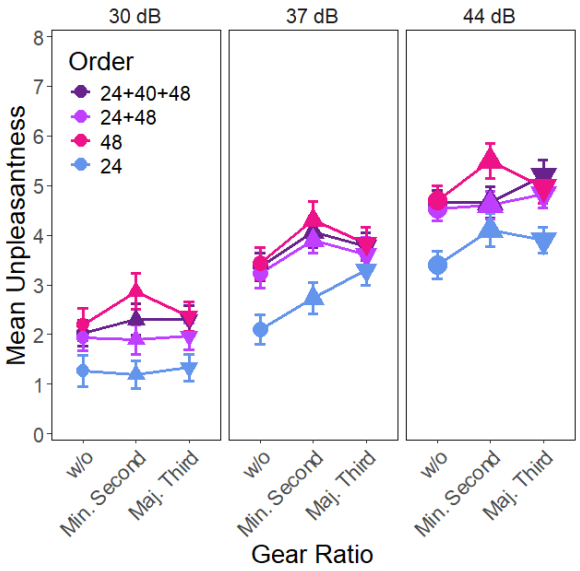

Figure 3: Mean unpleasantness ratings (N=30). Errorbars show standard errors.

ings, indicating that additional gear orders have a different impact depending on the underlying motor orders. Figure 4 shows a different arrangement of the results to allow for a direct comparison between the average ratings for unpleasantness and tonality. Here, the subplots are linked to the order composition of the tonal signature. For the single tone with the higher order (48th order), the unpleasantness ratings are overall above the tonality ratings whereas similar values for tonality and unpleasantness are found for the lower single tone order (24th order). For the combined orders (24+48 and 24+40+48) and higher tone levels, the tonality ratings are higher than the unpleasantness ratings, indicating an integration of tonality across the number of partials while the unpleasantness seems to be driven mostly by the highest frequency present.

Relationship between tonality and unpleasantness ratings

Figure 5 shows that the average unpleasantness and tonality ratings are overall highly correlated with each other (Pearson $r = .96$, $p < .001$), which can be mainly explained by the large effect of the tone level. Across all tonality rating values, the high frequency single tone of the 48th order alone was more unpleasant than the other sounds when being rated similarly in terms of tonality. Although the 48th order is 6 dB lower in level than the 24th order, the local tone to noise ratio is higher because of the 12 dB/oct. decay of the background noise and together with the higher frequency seems to drive the unpleasantness. Furthermore, sounds having multiple tonal components (24+48 and 24+40+48) can be more pleasant than the single tones while having a similar tonality rating. The other way around, sounds consisting of multiple tones received higher tonality ratings than sounds containing single tones when being similarly unpleasant.

Discussion and Conclusion

Some of the used parameters and parameter ranges of this study are close to the work by Doleschal et al. [10]. Similar to their results, statistically significant main effects were found for the present tonality ratings for the parameters tone level and order composition. In the present study, the additional gear ratios affected the tonality and unpleasantness but no difference between the two ratios was found. Including only a single additional tone relative to the lowest order limits the amount of resulting beats which might explain the rather small effect here, whereas larger effects are found for sounds with more harmonics and an interval tone each [6]. The unpleasantness judgements and tonality ratings were generally highly correlated with each other but the relationship suggests that the listeners applied different criteria for the tonality ratings and the unpleasantness judgements. In detail, the results suggest that the 48th order was more unpleasant than the 24th order when rated similarly in terms of tonality. This result is well in line with ratings for pure sinusoids [4] as well as single sinusoids embedded in uniformly masking noise [3], where the growth in unpleasantness was also stronger than the increase in tonality for frequencies above about 1 kHz. Furthermore, the present results suggest that sounds containing single orders can be more unpleasant than sounds containing multiple orders despite being rated similarly or even higher in terms of tonality. Apparently, the growth in tonality is stronger than the increase in unpleasantness for sounds containing multiple tonal orders compared to the single order case.

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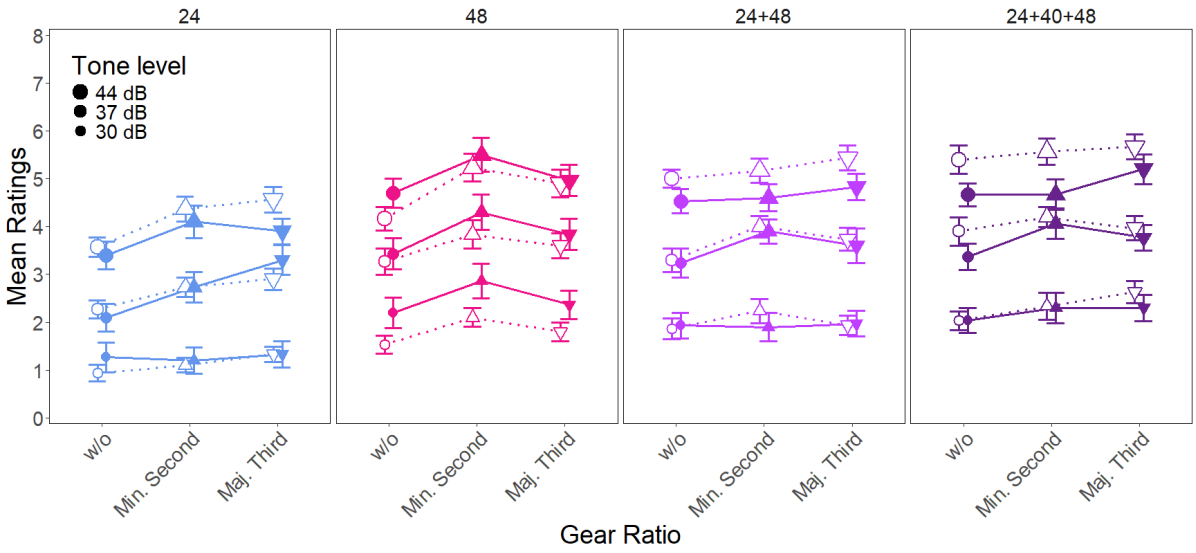

Figure 4: Mean tonality (open symbols, dashed lines) and unpleasantness (filled symbols, solid lines) ratings (N=30). Errorbars show standard errors. Subplots indicate the motor order configuration.

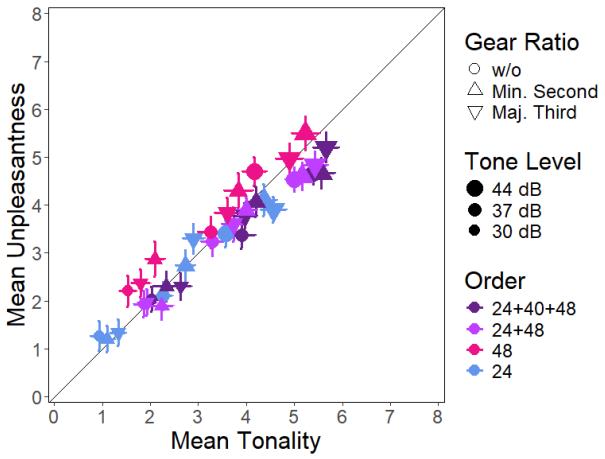

Figure 5: Relationship between mean tonality and unpleasantness ratings (N=30). Errorbars show standard errors.

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References

[1] Lennström, D., Lindbom, T., Nykänen, A. (2013) Prominence of tones in electric vehicle interior noise. Proc. Inter-Noise 2013, Innsbruck, 589-596.

[2] Lennström, D., Gutierrez Melian, A., Nykänen, A., Becker, J., Sottek, R. (2019) Perception of tones below 1 kHz in electric vehicles. Proc. Inter-Noise 2019, Madrid, 3675-3685.

[3] Parizet, E., Bolmont, A., Fingerhuth, S. (2009) Subjective evaluation of tonalness and relation between tonalness and unpleasantness. Proc. Inter-Noise 2009, Ottawa, 934-941.

[4] Sottek, R., Becker, J. (2019) Tonal annoyance vs. tonal loudness and tonality. Proc. Inter-Noise 2019, Madrid, 6977–6986.

[5] Oetjen, A., Volk, P., van de Par, S. (2015) Tonality perception of stationary and transient signals. Proc. Euronoise 2015, Maastricht, 1913-1918.

[6] Rieger, A., van de Par, S., Rabl, H.-P., Oetjen, A. (2023) The contribution of selected auditory sensations to the prediction of preference judgements for consonant and dissonant sounds. Proc. Inter-Noise 2023, Chiba, 5833-5841.

[7] Vormann, M. (2011) Untersuchungen zu Psychoakustischen Mess- und Berechnungsverfahren der Tonhaltigkeit. PhD-Thesis, Carl von Ossietzky Universität Oldenburg.

[8] Hansen, H., Weber, R. (2011) Partial loudness as a measure of the magnitude of tonal content. Acoustical Science and Technology 32, 3, 111-114.

[9] Hansen, H., Verhey, J. L., Weber, R. (2011) The magnitude of tonal content. A review. Acta Acustica united with Acustica 97, 355-363.

[10] Doleschal, F., Rottengruber, H., Verhey, J. L. (2021) Influence parameters on the perceived magnitude of tonal content of electric vehicle interior sound. Applied Acoustics 181, 108155.

[11] Bugl, B., Rabl, H.-P., Töpken, S., Claaßen, E., van de Par, S., Rieger, A. (2025) Implementation of a synthesis tool for stationary and non-stationary interior noise. Proc. DAS—DAGA 2025, Copenhagen, 1499-1502.

[12] Töpken, S., Claaßen, E., van de Par, S., Rabl, H.-P., Bugl, B., Rieger, A. (2025) Tonality ratings and unpleasantness judgements for synthesized EV acceleration sounds. Proc. Aachen Acoustics Colloquium 2025, Aachen, pp. 1-8.