DOI: 10.71568/daga2026.557

Psychoacoustic Dissonance Theory Supported in Listeners' Ratings of Synthesized Electric Vehicle Acceleration Sounds

Anna Rieger[1,2], Benedikt Bugl[1], Sabrina Freisleben[1], Hans-Peter Rabl[1], Stephan Töpken[2], Eike Claaßen[2], Steven van de Par[2], Arne Oetjen

[1] *OTH Regensburg, 93053 Regensburg, Germany, Email: anna.rieger@othr.de, anna.rieger@uol.de*

[2] *Carl von Ossietzky Universität Oldenburg, Department of Medical Physics and Acoustics, Acoustics Group and Cluster of Excellence "Hearing4all", 26129 Oldenburg, Germany*

Introduction

Dissonance is a central concept in music theory and auditory perception. Within western music theory, pitch relationships are commonly described in terms of a discrete system of twelve tones per octave, in which specific notes and intervals are traditionally associated with either consonance or dissonance. [1]

In vehicle acoustics, tonal components are known to play an important role in the subjective evaluation of sound quality. Many studies have examined how tonal prominence influences the unpleasantness of sounds as a measure of overall sound quality, e.g. [2, 3]. By contrast, the role of relationships between tonal components, particularly frequency intervals and the resulting perception of dissonance, has received less attention in a technical context. This gap is relevant because technical systems often generate several tonal components whose spectral interaction may shape perceived sound quality beyond the effect of tonality alone.

One example is the drivetrain in electric vehicles, where the electric motor is typically coupled to one or more gearbox stages. Both, the motor and the gearbox can generate characteristic tonal components, with fundamental frequencies and their harmonics. Because these components are linked through the transmission ratio, different gear ratios lead to different interval structures, which may in turn affect the perceived dissonance of the emitted sound.

The present study examines how the spectral composition of tonal components influence perceived dissonance and unpleasantness in synthesized electric motor run-up sounds with different gear ratios. By focusing on systematically varied tonal structures, the study seeks to clarify whether knowledge derived from music theory can be transferred to a psychoacoustic concept of dissonance and how consonant and dissonant structures affect the perceived unpleasantness of sounds.

Methods

Listening experiments were conducted on two separate days. Participants evaluated the presented sounds with respect to unpleasantness and perceived dissonance. At the beginning of each session, written instructions were provided to explain the respective task.

Before the dissonance evaluation, participants received an additional introduction to the concept of dissonance supported by auditory examples. To illustrate different degrees of dissonance, musical intervals arranged according to their theoretical dissonance were presented using piano sounds and synthesized pure tones. Pink noise was also included as an example of a non-tonal stimulus, together with mixtures of pink noise and synthesized tones.

Both the dissonance and unpleasantness tasks were preceded by an orientation phase in which selected stimuli were presented to familiarize participants with the range of sound characteristics and dynamic variations represented in the stimulus set.

Ratings in both experiments were collected on a nine-point scale ranging from 0 ("not") to 8 ("very").

Stimuli

A total of 185 synthesized sounds were prepared for the listening experiments. The stimulus parameters were selected based on the analysis of measurements provided by industry partners associated to the project, as well as findings from the literature.

The signals contained run-ups from 250 to 2500 rpm over a duration of 8 s. All stimuli contained the same background noise to which tonal components were added. The spectrum of the background noise was approximately flat up to 40 Hz and decreased above this frequency with a slope of about 12 dB/oct. The sound pressure of the noise increased linearly throughout the run-up and reached a level of 74 dB SPL at the end of the stimulus.

Tonal components representing motor orders were embedded in the broadband noise. The components were implemented as linear frequency sweeps and comprised either single or multiple orders (24th, 48th, 24th+48th, and 24th+40th+48th). Accordingly, the 24th order increased from 100 Hz to 1 kHz, whereas the 48th order covered a range from 200 Hz to 2 kHz. The level of the 24th order was adjusted to three values, namely 25, 32, and 39 dB SPL, and remained constant within each run-up condition. The levels of the higher orders followed a spectral decay of -6 dB/oct relative to the 24th order. Thus, whenever present, the 48th order was 6 dB lower than the 24th order. The lowest tonal level was chosen such that tones were only slightly audible. The highest level exceeded values typically expected in the interior of an electric vehicle.

In addition to the motor orders, the synthesized run-ups

either contained no gear-related tonal components or one to two additional gear orders. These were selected such that they formed frequency relationships with the lowest motor order that can be described as either consonant or dissonant. An overview of the corresponding intervals is given in Table 1.

Table 1: Configuration of tonal structures in run-up sounds: Frequency Intervals depicted from left to right with their interval name, the mathematical definition in music theory (equal tempered scale), as well as the rounded decimal number and categorization into consonant or dissonant.

Interval Name	Interval	Decimal	Category
Min. Second	$2^{1/12}$	1.06	diss.
Maj. Third	$2^{4/12}$	1.26	cons.
Fourth	$2^{5/12}$	1.34	cons.
Tritone	$2^{6/12}$	1.41	diss.
Min. Seventh	$2^{10/12}$	1.78	diss.

Figure 1 illustrates example spectrograms for two stimuli containing the 24th and 48th motor orders together with one additional gear order at the highest tonal level of 39 dB SPL. In the upper part of the figure, the resulting interval corresponds to a Minor Second, which is commonly regarded as dissonant in music theory. In the lower part of the figure, the interval is a Fourth, typically classified as consonant.

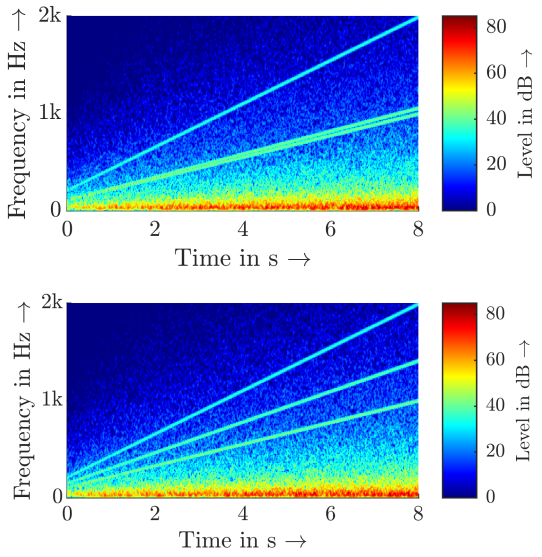

Figure 1: Exemplary sounds of the listening experiment in the highest tone level of 39 dB. Upper part: 24th and 48th order, with a gear order corresponding to a dissonant interval Minor Second. Lower part: 24th and 48th order, with a gear order corresponding to a consonant interval Fourth.

The stimulus set further included a noise condition without any tonal components. Additional synthesized variants with structural resonances and other interval manipulations were also part of the experiment, but these are not shown in the present paper, as well as results for sounds with a single 48th motor order.

Listening Setup

The listening tests were conducted in a sound-attenuated booth. Stimulus presentation was realized using Matlab, with playback through Sennheiser HD650 headphones connected to an RME Fireface UFX III audio interface. Prior to the experiment, the reproduction chain was calibrated with a GRAS 43AA-S2 CCP ear simulator using a 1 kHz reference tone at a specified level. To avoid abrupt onset and offset artifacts, all stimuli were shaped with 20 ms raised-cosine windows.

Participants

A total of 30 participants (12 female, 18 male) took part in the listening experiments. Their ages ranged from 20 to 40 years, with a mean age of 28 years. All 30 participants reported normal hearing. Ethical approval was obtained from the Joint Ethics Committee of Bavarian Higher Education Institutions (GEHBa; reference GEHBa-202405-V-186). For the data analysis, the responses of two participants were excluded because their individual ratings showed correlation coefficients of $R < 0.1$ with the overall response of the sample.

Results

The analyses presented in this contribution exemplarily show dissonance and unpleasantness ratings only for the medium tonal level of 32 dB. For the other tonal levels (25 dB and 39 dB), the results show that higher tone-to-noise ratios generally lead to increased dissonance ratings, largely independent of the specific interval. Such a level dependence is not described in classical musical interval theory. However, similar effects are known from other psychoacoustic attributes such as tonality, for which a higher level of the tonal component is likewise associated with a stronger perceptual prominence [4].

Dissonance Ratings

Figure 2 presents the results for selected sounds at a tonal level of 32 dB. The x-axis represents the frequency intervals between the 24th base order and the interval tone associated with a gear order. All sound groups (purple, blue and orange) with white faced data points have one interval tone. The sound group with blue faced data points is the only exception where both, the 24th and the 48th order, have an interval tone with the frequency interval labeled on the x-axis.

The results reveal clear differences in perceived dissonance depending on the frequency interval and the composition of the tonal structure. For sounds without any additional interval tone, the stimulus containing only the 24th order was rated as only weakly dissonant. Adding the 48th order led to higher dissonance ratings, although the resulting 2:1 frequency ratio would not be considered dissonant from a music-theoretical perspective. The stimulus containing the 24th, 40th, and 48th orders was rated as even more dissonant, which can be attributed to the 40th order forming intervals with the 24th and 48th order. When an additional interval tone corresponding to a Minor Second was introduced, all sound configurations received the highest dissonance ratings, in line with expectations from music theory. For Thirds and Fourths, dissonance ratings were lower consistently across all tonal

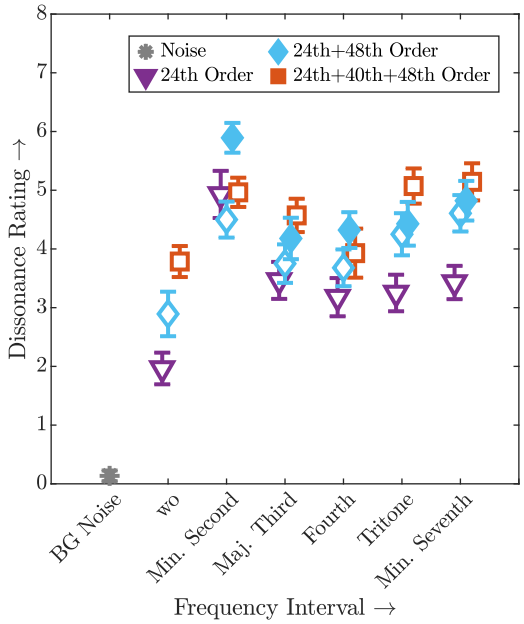

Figure 2: Mean dissonance ratings (N=28) for a tone level of 32 dB. Errorbars show standard errors. White faced data points: one interval tone. Blue faced datapoints: two interval tones.

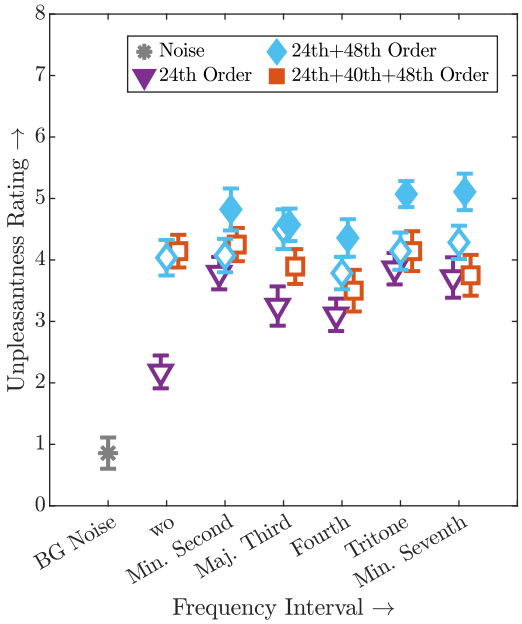

Figure 3: Mean unpleasantness ratings (N=28) for a tone level of 32 dB. Errorbars show standard errors. White faced data points: one interval tone. Blue faced datapoints: two interval tones.

configurations, showing good agreement with the musical classification of these intervals. Larger deviations from music theory emerged, however, for the Tritone and the Minor Seventh. In sounds based only on the 24th order, these intervals were not rated as more dissonant than the Third or the Fourth. In contrast, for sounds based on the 24th, 40th, and 48th orders, both intervals were rated as dissonant as the Minor Second. This indicates that the perceptual evaluation of dissonance in these technical sounds cannot be explained by interval categories alone, but strongly depends on the overall tonal structure.

Unpleasantness Ratings

Figure 3 presents the unpleasantness ratings for the same set of sounds shown in Figure 2.

A comparison of the dissonance and unpleasantness ratings suggests that both attributes represent distinct perceptual dimensions for the participants. While the frequency intervals appear to be a dominant factor in the evaluation of dissonance, resulting in pronounced maxima and minima across the interval conditions, the trends in unpleasantness are less distinct. There is an overall tendency for sounds containing consonant intervals to be judged as less unpleasant than those containing dissonant intervals. One particularly notable finding is that, across all interval conditions, the sound based on the 24th and 48th orders with two additional interval tone was consistently rated as the most unpleasant. A key difference of this stimulus is that, due to the additional interval tone, it also contains the highest absolute tonal frequencies among the compared sounds. This observation is in line with previous studies reporting that increasing psychoacoustic sharpness, or more specifically tonal sharpness, contributes to greater unpleasantness [5].

Psychoacoustic Concept of Dissonance

Beyond the musical perspective on frequency intervals, these findings illustrate how dissonance is judged for synthesized technical sounds in a psychoacoustic experiment. As shown in the results, some frequency intervals are rated in a way that is overall consistent with interval categories known from music theory, such as Seconds, Thirds, and Fourths. However, other intervals, including the Tritone and the Minor Seventh, show markedly different perceptual outcomes depending on the composition of the tonal structure.

However, when there is only one additional tonal component relative to the 24th-order base tone, these intervals did not increase perceived dissonance, whereas a clear increase in dissonance was observed for more complex tonal structures, such as the combination of the 24th, 40th, and 48th orders. This behavior can be explained well by the processing characteristics of the human auditory system and, more specifically, by mechanisms underlying the perception of modulation. A common explanatory approach of dissonance perception assumes that audible envelope fluctuations, i.e., beating caused by closely spaced and interfering partial tones, contribute substantially to increased dissonance perception. Figure 4 schematically illustrates this idea by showing tones associated with motor orders in relation to tones associated with gear orders on the example of two specific intervals (Minor Second and Tritone), represented as constant-amplitude components across auditory filters. For this schematic representation, the base tone was set to 500 Hz, which was a mean frequency in the real run-up sounds.

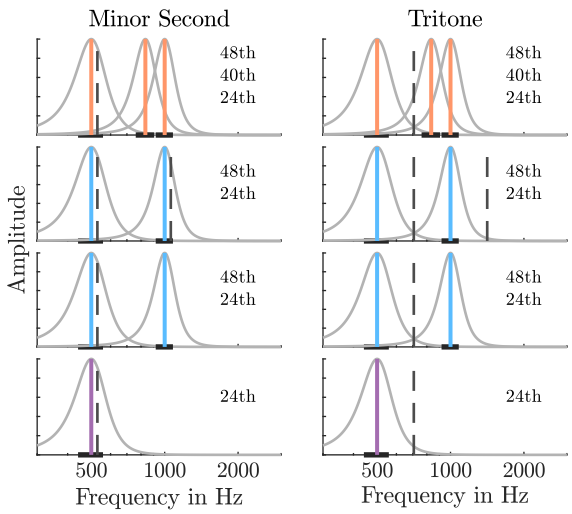

Figure 4: Schematic representation of tonal components in auditory filters, relating to cochlea functionality. Solid colored lines correspond to base orders, while dashed lines indicate the additional interval tones.

When comparing the representation used in this figure to the dissonance ratings and of the intervals Minor Second and Tritone shown in Figure 2, it is apparent that dissonance increases whenever two tonal components are located close to each other within the same auditory filter. For example, the sound containing the 24th and 48th orders together with two interval tones corresponding to a Minor Second differs significantly from the other sounds with only one interval tone at the same interval, since these latter sounds contain only one pronounced beating component. A similar pattern can be seen for the Tritone: The sound based on the 24th, 40th, and 48th orders is expected to produce the highest dissonance because it contains the largest number of closely spaced tonal components and therefore the strongest beating interactions. This also explains why the theoretically dissonant Tritone does not lead to increased dissonance in the case of the single 24th-order sound. In that condition, the base tone and the interval tone are too far apart in frequency to generate strong beating components. This schematic static representation provides a useful basis for explaining individual dissonance ratings even of time-varying run-up sounds.

In contrast to the rather sparse tonal structures considered here, musical instruments typically exhibit rich harmonic spectra, so that playing a note almost inevitably produces multiple interfering partial tones and therefore beating components, which helps explain why interval theory is generally applicable in the musical context. Furthermore, the psychoacoustic concept of dissonance should not be confused with the psychoacoustic concept of roughness. In [6] this distinction is discussed in more detail and also illustrates how both percepts differ with respect to modulation frequencies in which their perceptual maxima occur. In addition, psychoacoustic modeling is also based on different model structures for dissonance, e.g. [1, 5, 7] and roughness, e.g. [8].

Summary

These results indicate that concepts from musical interval theory only partially describe psychoacoustic dissonance in technical sounds. Although some interval effects are consistent with music-theoretical expectations, the perceptual outcome depended strongly on the complete tonal structure, especially for sounds with only few tonal components. To explain the observed ratings, it is therefore necessary to consider the overtone structure and the occurrence of closely spaced interfering partial tones that may generate audible beating within auditory filters. In this sense, the dissonance ratings were well explained by established psychoacoustic concepts of auditory processing. The comparison with unpleasantness ratings further suggests that unpleasantness is shaped by multiple psychoacoustic attributes, including loudness, sharpness, tonality, and dissonance, rather than by interval-related dissonance alone.

Acknowledgement

The authors gratefully acknowledge the financial support of the research project AudioOpt by the Federal Ministry for Research, Technology and Space within the framework of the VIP+ funding program (contract number 03VP11931). The authors also thank the industry partners from the automotive sector for valuable discussions on the topic.

References

[1] Sethares, W. A. (2005). Tuning, Timbre, Spectrum, Scale, 2nd ed. (Springer, London).

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

[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] Fastl, H., and Zwicker, E. (2007). Psychoacoustics: Facts and Models, 3rd ed. (Springer, Berlin Heidelberg).

[5] 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.

[6] Ambrazevičius, R. (2016). "Dissonance/roughness and tonality perception in Lithuanian traditional Schwebungsdiaphonie" Journal of Interdisciplinary Music Studies 8(1&2), 39–53.

[7] Rieger, A., Oetjen A., Van de Par S. and Rabl, H.-P. (2021). Gehörbezogene Modellierung der Dissonanz. Fortschritte der Akustik - DAGA 2021, Wien, 1034-1037.

[8] DIN 38455: Calculation of the auditory sensation roughness, November 2024.