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Tonality and Unpleasantness Ratings for Excerpts and Overall Acceleration Sounds of Electric Vehicles

Eike Claaßen[1], Florian Kanzler[1], Benedikt Bugl[2], Anna Rieger[2], Hans-Peter Rabl[2], Stephan Töpken[1], Steven van de Par[1]

[1] *Carl von Ossietzky Universität Oldenburg, Department of Medical Physics and Acoustics, Acoustics Group and Cluster of Excellence "Hearing4all", Ammerländer Heerstraße 114-118, 26129 Oldenburg, Germany*

[2] *OTH Regensburg, 93053 Regensburg, Germany*

Email: eike.claassen@uol.de

Introduction

The interior sound of electric vehicles (EV) often contains tonal components. Typical sources for tonal sound components can be the electric engine, the gearbox, or the inverter. Structural resonances of the chassis can further alter tonal components. In studies, it was found that tonal components can, depending on the driving condition and sound source negatively affect the perceived sound quality [1, 2].

A common method to asses the acoustic quality of vehicle sounds are listening experiments in which participants rate real or artificial vehicle sounds. In many cases the stimuli used in the listening experiments have a duration of several seconds and contain single or multiple transient tonal components and are evaluated by participants in rating experiments [3, 4, 5].

In particular, when the level or frequency of tonal components changes over the duration of the stimulus, the question arises which time intervals are relevant for evaluating the overall signal. In literature, the relationship between overall judgments and instantaneous judgments was mainly investigated for loudness. Kuwano and Namba found that the overall judgments for loudness does not correspond to the average loudness but is related to instantaneous loudness surpassing a certain level [6]. Västfjäll found that in the context of airplane noise sounds with a total duration of 90 s participants preferred stimuli that ended with a low sound pressure level over those with a high sound pressure level [7]. Both studies however link changes in level to the assessment of the overall loudness or preference.

In this study ratings of tonality and unpleasantness for artificial vehicle acceleration sounds were collected. Test subjects evaluate 8-second acceleration sequences as well as 1-second excerpts from the long acceleration sequences, providing insights into the instantaneous assessment. Further this study evaluates whether an approximation with stationary excerpts leads to similar tonality and unpleasantness ratings.

Stimuli

For this study, artificial electric-vehicle acceleration sounds were generated that resemble an acceleration process from 250 to 2500 RPM with a duration of 8-seconds [8]. The artificial sounds consisted of a tonal component simulating the 24th and 48th motor order embedded in a background noise that, above 40 Hz, decays by 12 dB per octave. The level of the tonal component (L_{Tonal}) is either 30 or 44 dB. Additionally the sounds can contain a structural resonance (SR) that boosts the level of the tonal components at frequencies of 500 Hz and 900 Hz by 15 dB resulting in a total of four base stimuli. Spectrograms for these four base stimuli are shown in Figure 1.

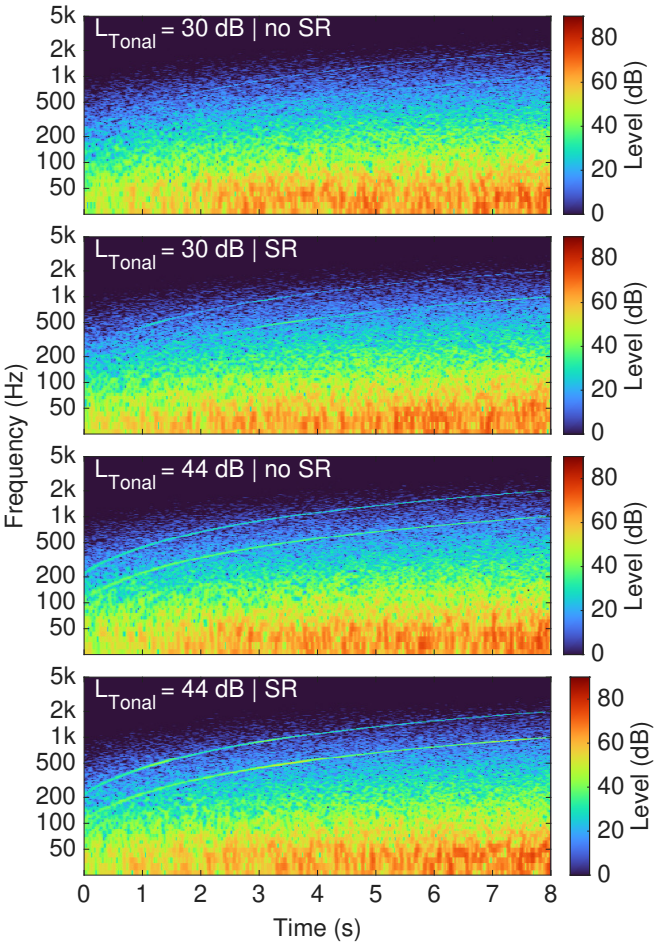

Figure 1: Spectrograms of the artificial vehicle acceleration sounds with a duration of 8 seconds. The sounds have tone-levels (L_{Tonal}) of 30 dB or 44 dB and feature either no structural resonances (no SR) or structural resonances that occur at 500 Hz and 900 Hz.

Each of the four base sounds was divided into eight semi-stationary excerpts with a duration of 1 second, resulting in 32 semi-stationary excerpts. For stationary versions of the excerpts, the frequency of the tonal component and the level of the background noise were set the average values of the corresponding semi-stationary segment.

Procedure

In listening experiments, participants rated the tonality and unpleasantness of stimuli in separate assignments on different dates. Half of the participants rated tonality on the first assignment, while the other half started with unpleasantness. On each assignment, the participants first rated the four long sounds with a duration of 8 seconds each. The stimuli rated in this first experiment contained the four base stimulus (Figure 1) and 21 additional sounds. After a short break the participants rated the short 1 second excerpts in a separate experiments. The 64 short 1 second excerpts used in this experiment were solely based on the base stimuli.

Participants rated the sounds on an equidistant 9-point scale labeled from 0 ("not at all") to 8 ("very"). The scale was an extension of a 5-point Rohrmann scale with unlabeled in-between categories labels [9].

Before each experiment, participants received a written instruction and an orientation phase in which a selection of the stimuli were presented via headphones. To introduce and define the concept of tonality, 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. Tonality was explained as the loudness of the tonal content (in German: "Lautheit des tonalen Anteils") as suggested by Hansen et al. [10, 11].

Apparatus

The listening experiments were conducted in a single-walled listening booth. The stimuli were presented diotically with open headphones (Sennheiser HD 650) driven by the headphone output of an audio interface (RME Fireface UC) that was connected to a computer. The experimental task was visualized using a graphical user interface. Participants could answer using a mouse, keyboard, or touchscreen in front of them. The calibration was carried out using a microphone (B&K Type 4134) in an Artificial Ear (B&K Type 4153) that was connected to a microphone amplifier (B&K Type 2669) and connected to a measurement amplifier (B&K Type 2610).

Participants

Twelve participants (6 female and 6 male) with a mean age of 26.4 years ranging from 21 to 39 years volunteered to participate in the experiment. The participants were mainly students from the University of Oldenburg and self-reported that they do not suffer from any kind of hearing impairment. The participants were compensated with 12 € per hour. The Research Ethics Committee of the University of Oldenburg had no objections regarding the study (Drs.EK/2024/019).

Results

Exemplary mean tonality ratings for one base sound with and without structural resonances and a L_{Tonal} of 30 dB is shown in Figure 2.

For excerpts without structural resonances the mean ratings for tonality increase over time, however for the last time block 7-8s the mean rating for tonality decreased in comparison to the time blocks 5-6s and 6-7s. However, the standard error found for the last time blocks is larger compared to the time blocks between 5 and 7 seconds.

In the time-blocks 1-2 s and 2-3 s where the 48th motor order passes the structural resonance at 500 Hz the tonality ratings for excerpts containing structural resonances were higher compared to excerpts without structural resonances by up to 1 categorical unit. In the time block 3-4 s where the 24th motor order passes the structural resonance at 500 Hz and the 48th motor order passes the structural resonance at 900 Hz, an increase of more than 2 categorical units was found. In the last time block 7-8 s the 24th motor order passes the structural resonance at 900 Hz, resulting in higher tonality ratings of 2 categorical units. This shows that higher tonal audibility due to an increases in tone-to-noise ratios caused by structural resonances leads to higher ratings for tonality.

The tonality ratings for long 8-second signals with and without structural resonances are of similar magnitude like the corresponding 1 second excerpts with the highest tonality.

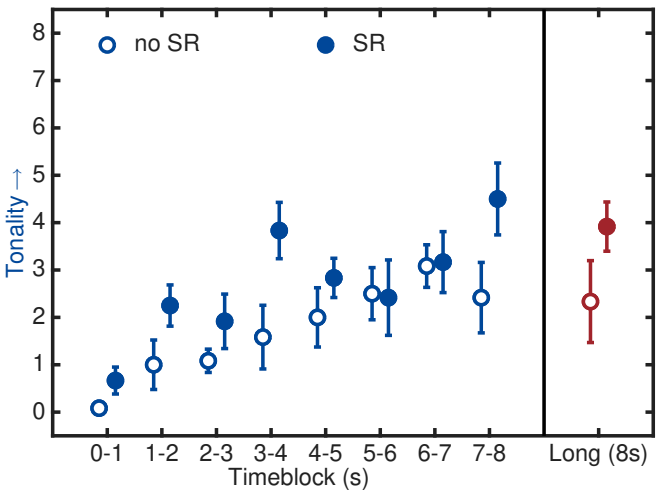

Figure 2: Mean ratings and standard errors for tonality. Ratings for the 1 second excerpts in blue and full 8 second stimuli in red. Open markers indicate a signal without structural resonances (no SR) and filled markers indicate a signal with structural resonances occurring at 500 Hz and 900 Hz (SR). The underlying signal has a maximum motor level (L_{Tonal}) of 30 dB.

The results for unpleasantness ratings are shown in Figure 3. In contrast to the results found for tonality the mean ratings for unpleasantness increase monotonously towards later time blocks for signals with and without structural resonances. The occurrence of structural resonances in the time blocks 1-2 s, 3-4 s, 4-5 s, and 7-8 s

leads to increased unpleasantness rating of up to 1.5 categorical units compared to excerpts that do not contain structural resonances.
The overall unpleasantness rating for the long 8 second sounds is approximately 1.5 categorical units below the highest unpleasantness rating of the 1-second excerpts.
For stimuli without structural resonances mean ratings for tonality and unpleasantness are, in most cases, of similar magnitude. However, when structural resonances occur, i.e., in the time blocks 3-4 s and 7-8 s, the increase in tonality over the signal without structural resonances is more than 2 categorical units, whereas the increase in unpleasantness is smaller than 1.5 categorical units. In the time block 2-3 s where the 24th motor order passes the structural resonance at 500 Hz and the 48th motor order passes the structural resonance at 900 Hz tonality ratings increase by more than 2 categorical units over signals without structural resonances whereas unpleasantness ratings increase by less than 1 categorical unit. This indicates that a temporal increase in tonal audibility more directly impacts the perceived tonality than it does the perception of unpleasentness.
Further, the results show that the standard errors found for unpleasantness ratings were larger compared to those found for tonality ratings, indicating that there seems to be higher interindividual agreement in the tonality ratings.
The comparison of the tonality and unpleasantness judgments between stationary and semi-stationary sounds is shown in Figure 4. The ratings are highly correlated for both tonality (Pearson $r = .97$, $p < .001$) and unpleasantness (Pearson $r = .98$, $p < .001$). The remaining variability from a one to one agreement is approximately the standard error found for the tonality and unpleasantness ratings. For the used excerpt duration of 1 second there is little to none difference in rating between the stationary and semi-stationary condition.

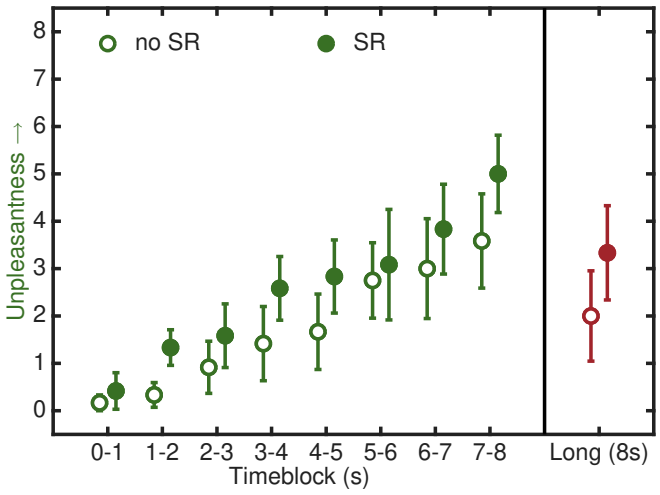

Figure 3: Mean ratings and standard errors for unpleasantness. Ratings for the 1 second excerpts in green and full 8 second stimuli in red. Open marker indicate a signal without structural resonances (no SR) and filled markers indicate a signal with structural resonances occurring at 500 Hz and 900 Hz (SR).

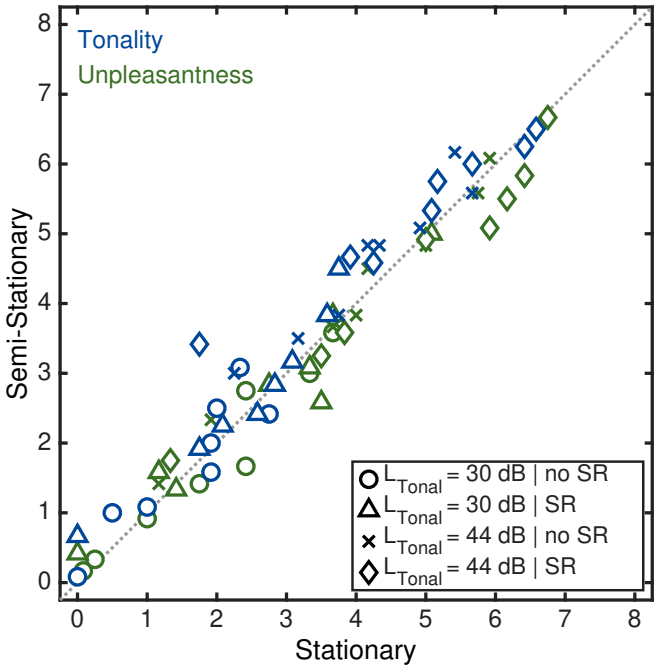

Figure 4: Relationship of mean ratings for stationary and semi-stationary excerpts. Ratings for tonality are visualized in blue and ratings for unpleasantness are visualized in green. A theoretical one-to-one agreement is visualized by a dotted gray line.

Discussion

In the present study, for excerpts without structural components the results showed an increase in the mean values for tonality and unpleasantness toward later time blocks. For the stimuli used in this study, the tonal component increases in frequency over time while the level of the background noise, above 40 Hz, decays by 12 dB/oct. Therefore, the last time blocks not only contain tonal components with the highest frequency but also with the least amount of spectral masking from the background noise, leading to a high tonal audibility. Similarly, time blocks containing structural resonances, and therefore having a higher local tone-to-noise ratio, were rated more tonal compared to the corresponding time blocks without structural resonances. These findings are in line with literature showing that tonality perception can increase with both the level and the frequency of the tonal component [12, 13]. The data indicates that the tonality, the loudness of the tonal content, for overall judgments is not the average over the temporal judgments but closer to the rating of the time blocks with the most prominent tonal content. Similar findings in the context of general loudness evaluations were made by Kuwano and Numba [6].

The ratings for unpleasantness increase towards later time blocks. For time blocks containing structural resonances, the increase in unpleasantness over an excerpt without a structural resonance is smaller compared to the ratings found for tonality indicating that increased tonal audibility during structural resonances under the tested conditions has only limited impact on unpleasantness judgements.

The results found in the current study indicate a high correlation and a close to one-to-one agreement between stationary and semi-stationary excepts both for tonality and unpleasantness ratings. This means that short stationary excerpts might be used as an approximation of transient signals given the present sweep slope. In the current study, the frequency of the tonal component increased by 113 Hz/s for the 24th motor order and 226 Hz/s for the 48th motor order. It is, however unclear if this would be still valid for signals with a faster sweep.

Summary

In the present study, ratings for tonality and unpleasantness were collected for synthesized acceleration sounds of electric vehicles. For the assessment of tonality, overall ratings of 8 s long acceleration sounds were closely linked to those found for the 1 second excerpts with the highest rated tonality. For the assessment of unpleasantness, on the other hand, the overall ratings were closer to the average rating across all timeblocks. Even tough ratings for tonality and unpleasantness are often found to be highly correlated, the perception of unpleasantness seems to be more complex. The results of the present study further show that stationary excerpts can serve as an approximation for temporal assessment of certain transient signals for frequency increases of up to 200 Hz/s.

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