Effect of tonality in loudness perception: Vacuum cleaner and shaver examples

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1. Introduction

Representing the intensity perception, loudness is the fundamental psychoacoustical unit [1]. Recent developments in calculation of the loudness result in standardization [2–4]. Available standards of ISO 532, DIN 45631 and ANSI S3.4 are proved to be efficient for understanding the threshold in quiet, masked thresholds and equal loudness contours. The term “loud” in language, on the other hand, might be rather complex when real complex signals are involved. As a listener, what we understand from the term “loud” is important and available models should be compatible with the intensity perceptions, since the main aim of any loudness models is to represent the attributes of intensity perception.

The effect of tonality on loudness perception is a known phenomenon and thoroughly investigated especially in the important works of Hellman [5–7]. All of the studies mainly focused on the different aspect of tonality on loudness, annoyance and noisiness judgments. Especially the investigations on loudness judgments are important for the comparison of the present study. In the first study [5] the effect of a single tonal component lying on top of a band signal is investigated. Low pass, flat and high pass band noise are combined with different tonal components in different levels, and tone-to-noise ratios and loudness, annoyance and noisiness judgments are investigated. Especially it is observed that the signals with low tone-to-noise values increase the overall loudness perception more than the signals with higher tone-to-noise ratios. The second study [6], as an extension to the first study, investigates the effect of the location of a single tone within the broadband noise. The effect of various partial masking produced by the tone in the noise is the focus of this study. Lastly, in the third study [7] instead of using a single tone, Hellman investigated the effect of two-tone-noise complexes. The frequency separation (Δf) of two tones is the main investigated parameter in this very last work, in difference to the former studies.

All those three studies give insight on the effect of tonality on overall loudness estimations by using synthesized signals and systematical inductive investigations. The main aim of the present study, on the other hand, is to understand the loudness perception of the real signals in a deductive way using the case studies of vacuum cleaners and shavers. Both noise sources are chosen due to their stationary noise characteristics. Moreover, comparison of the subjective evaluations with standardized loudness models are also investigated within the present study. In a recent study [8], efficiency of two loudness models are also compared by using broadband noise, and discrepancies between estimations and calculations are mentioned. The effect of other psychoacoustical parameters on loudness perception is also investigated in this study.

2. Sound samples

For the vacuum cleaners and shavers, some particular stimuli are selected from a broad stimuli pool, such that, the calculated loudness values are arranged within a proper order, i.e. not having too much differences between the successive stimuli. Vacuum cleaners are recorded in an anechoic chamber with a reflecting surface underneath, both with and without carpet conditions. Shavers are on the other hand recorded in the idle running mode, without any contact with skin surface, 15 cm away from the ear position. 15 vacuum cleaner stimuli and 23 shaver stimuli are selected for the listening tests.

Vacuum cleaners have usually some tonal components added to the broadband characteristics. Shavers, on the other hand, are basically the noise sources with multiple tonal components lying on top of each other. For some frequency ranges, tonal components are close to each other, hence the noise has its usual rough characteristics. Three example spectrograms of selected vacuum cleaners and electric shavers are given in Figs. 1 and 2. They show the lowest, middle and highest calculated loudness values from left to right for both devices.

3. Listening tests

20 participants take part in the listening tests, 7 woman and 13 men aged between 22 and 66. Stimuli are presented to the participants through Sennheiser HD600 headphones in a sound attenuating room. The presentation of the stimuli is random and 5 stimuli are used as training stimuli. Each stimulus is repeated three times, to check inter-individual validity. The subjects are asked to evaluate the loudness of the sounds on a quasi-continuous scale (from 0 to 100) with equidistance neighboring categories (not at all, slightly, moderately, very, extremely).

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4. Calculated loudness values

Figures 3 and 4 show the loudness values for vacuum cleaner and shaver stimuli, respectively. For the vacuum cleaners, calculated loudness values according to DIN 45631, are between 7.8 and 38.5 sone; and for the shavers between 7.4 and 15.1 sone. ISO 532 and DIN 45631 standards show almost the same results, while ANSI S3.4 standard produce the results higher than the other two standards [2–4]. For the vacuum cleaners, the overall trend of the three standards appear to be same, with ANSI S3.4 values systematically higher than the other two standards. For the shavers, on the other hand, the overall observed trend from DIN 45631 and

5. Estimations vs. calculations

The calculated (DIN 45631) and estimated loudness values for vacuum cleaner and shaver stimuli are shown in Figs. 5 and 6. Since all models show the same tendency but

ISO 532 standards cannot be observed for ANSI standard. The sorting order of the stimuli based on ANSI S3.4 differs from the other standards for multiple stimuli.
with shifted values, comparison of the estimations and calculations are done by using the loudness values calculated with the DIN 45631 standard. The dotted lines in both figures show the trend lines of both estimations and calculations. For the sake of visualizations, the range of both \( y \) axes in the double-\( y \) plots are chosen in a way that the trend lines of estimations and calculations have same slopes and intercepts. Hence it is possible to observe the similar tendencies between estimations and calculations as well as possible discrepancies. Error bars represent standard deviations. For the vacuum cleaners estimations and calculations show good correlation. For the shavers, on the other hand, stimuli 1, 21 and 22 are found to be systematically lower than the calculated loudness values according to DIN 45631.

6. Psychoacoustical parameters
In order to understand the possible effect of other psychoacoustical parameters, sharpness, roughness and tonality values are calculated for each 23 shaver stimuli. Figure 7 shows sharpness and roughness values, where Fig. 8 shows tonality values for shaver stimuli. Sharpness calculations are based on DIN 45692 standard, roughness calculations are based on Aures model and tonality calculations are based on the publications by Terhardt and Aures [9–12].

7. Results and discussion
Vacuum cleaner and shaver sounds are used as a case study to understand the loudness perception of real signals and compare this perception with available loudness models. 15 vacuum cleaner and 23 electric shaver sounds are selected in this study, from a broad stimuli pool, hence the calculated loudness values of the selected stimuli are arranged with a proper order, not having too much difference between successive stimuli.

For the listening tests, the category scaling method is used with a quasi-continuous scale with verbal anchors, for both cases. Participants are asked directly “how loud is that sound?” without giving any further definition of loudness, to make sure that the results are free from bias.

The standard deviations of loudness estimations of vacuum cleaners show lower values than electric shavers. The reason can be explained as the available loudness range of the vacuum cleaners being bigger than the loudness range of electric shavers. However, it is still observed during the listening tests that the subjects are able to evaluate the loudness mainly based on the intensity perception, not considering the spectral characteristics of sound in general.

Estimations and calculations (according to DIN 45631) show high correlation for vacuum cleaners, but for the shavers, especially stimuli 1, 21 and 22 show systematically lower loudness estimations. Intensity perception for these particular stimuli is systematically lower than the calculated loudness values. To understand this fact, sharpness, roughness and tonality values are calculated for electric shavers.

No specific correlation is observed between sharpness and roughness with the loudness estimations. On the other hand, calculated tonality values, for stimuli 1, 21 and 22 are quite lower than the other stimuli. Figures 9 and 10 show as an

![Fig. 9 Frequency content of the stimuli 20.](image)

![Fig. 10 Frequency content of the stimuli 21.](image)
example, two neighboring stimuli, 20 and 21, for shavers. Calculated loudness values for stimuli 20 and 21, for DIN 45631, are 13 and 13.2 sone, respectively. Averaged estimations amongst 20 participants are 84 points for stimulus 20 and 50 points for stimulus 21. Table 1 shows the overall comparison of those two stimuli.

It is concluded, that the absence of tonal components, when compared to the other stimuli in the stimuli pool, yield in lower intensity perception. When more tonal components in a critical band are present, in comparison to a broad band noise falling in the same critical band, calculated loudness for the broadband noise is higher than the estimated loudness results. This observation can be taken into account for calculating loudness values of real signals, when the tonal components present for representing the intensity perception of majority of the listeners without hearing impairments.

### Table 1  Comparison of two neighboring shaver stimuli, 20 and 21.

<table>
<thead>
<tr>
<th>Stimuli No.</th>
<th>SPL [dBA]</th>
<th>Loudness (DIN 45631) [sone GF]</th>
<th>Loudness estimations [scale 0–100]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>58.7</td>
<td>13</td>
<td>84 points</td>
</tr>
<tr>
<td>21</td>
<td>62.1</td>
<td>13.2</td>
<td>50 points</td>
</tr>
</tbody>
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### References