

Annoyance Modelling of Canister-Type Vacuum Cleaner Noise

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Motivation

The vacuum cleaner market offers a wide array of options, varying in features such as price and efficiency. Among these variations, the difference in sound power levels stands out prominently, as indicated by the declared levels on energy labels. However, alongside these sound power level differences, it is apparent that there exist spectral variations among vacuum cleaners. This study aims to investigate, assess, and subsequently incorporate the influence of these spectral differences on annoyance perception in a multiple linear regression model. This model can be used as a benchmarking tool for manufacturers, to assess the relative sound quality of the device under test.

To maintain clarity and focus, investigation was limited solely on canister-type vacuum cleaners. Robot vacuum cleaners, upright vacuum cleaners, handheld vacuum cleaners or wet-type vacuum cleaners were not in the scope of this work.

Methodology

15 different vacuum cleaners were selected with the observation of variations in the declared sound power levels. These levels ranged from approximately 59 dB to 82 dB, aligning with the scale observed in market observations. The declared sound power levels of the selected vacuum cleaners can be found in Figure 1. For some points, there were more than one vacuum cleaners available.

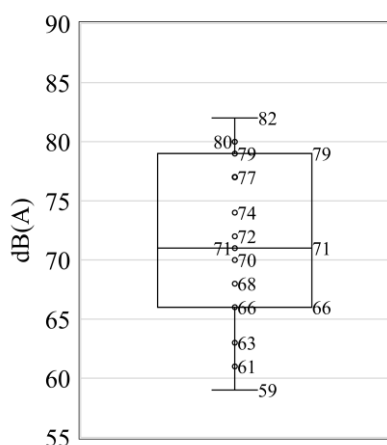


Figure 1: Distribution of the declared sound power levels of the vacuum cleaners used in the study in dB(A).

The 15 selected vacuum cleaners were recorded on a reflective surface and on top of a carpet as specified in IEC

60704-2-1 [1]. The recordings of the vacuum cleaners were done at their maximum operating power. The spectrograms of the 15 vacuum cleaner noise on hard floor can be found in Figure 3. As observed, notable differences exist in level among the recordings, variations in tonality, particularly across different frequencies, and differences in what may be referred to as spectral centroid or sharpness.

Listening Tests

To assess the impact of spectral differences on annoyance perception among the devices, two listening tests were conducted. The first test involved the use of original sounds obtained from recordings made on reflective surfaces and carpets. In the subsequent test, these sounds underwent manipulation, with new sounds added to increase variations in acoustic and psychoacoustic parameters. Specifically, the manipulations were aimed at reducing levels, reflecting the potential for quieter devices in the future.

Both listening tests were conducted online using the online listening experiment platform of Chair of Acoustics and Haptics, TU Dresden, by using the category scaling method with verbal anchors. This method employs a slider with verbal anchors, dividing values between 0 and 100 in 1-step intervals. Figure 2 shows the user interface used in the experiments. During the listening experiments, participants were asked to evaluate the annoyance of the sound samples.

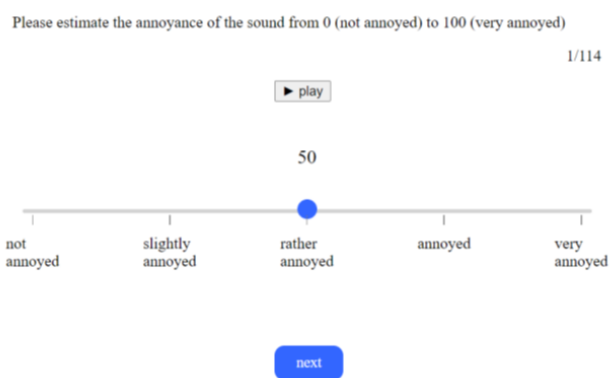


Figure 2: User interface used in experiments.

Stimuli

The first listening test comprised 30 stimuli, including recordings of 15 chosen vacuum cleaners on both hard surface and carpet. Subsequently, in the second listening test, new manipulated signals were introduced alongside these stimuli, resulting in 92 stimuli.

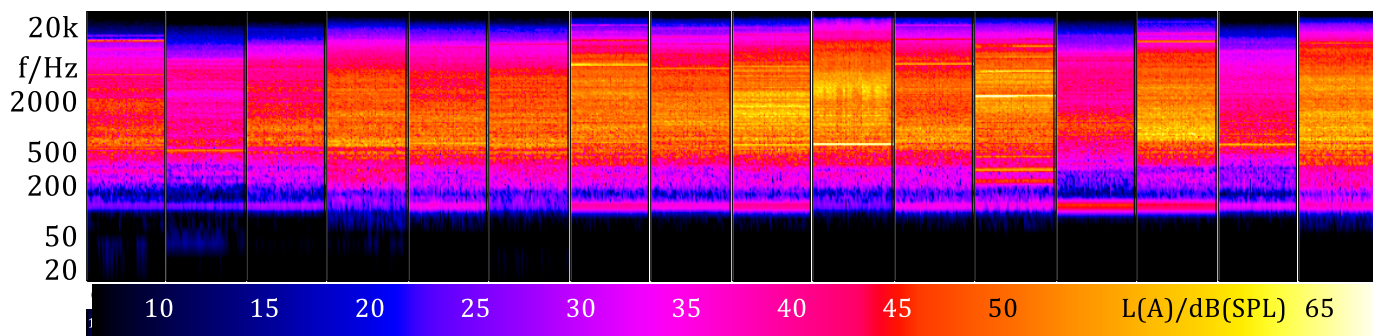


Figure 3: Spectrograms of 15 vacuum cleaners on hard floor.

These variations were generated through adjustments including increasing or decreasing the overall level of the stimulus, filtering out dominant tonal components, and applying low-pass filtering to increase variability in the loudness/sharpness relationship. The dB(A) distributions of the stimuli used in both listening tests can be found in Figure 4. As can be seen, in the second listening test, after the manipulations, lower level signals were also included in the test.

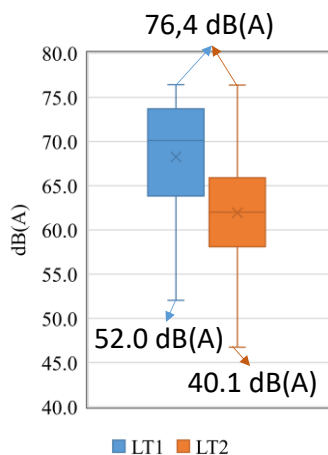


Figure 4: Distributions of dB(A) values for stimuli used in listening test 1 (LT1) and listening test 2 (LT2).

Results

20 people took part in the first listening test, aged between 19 to 67, with a mean age of 29 and a standard deviation of 11.8. Furthermore, 21 participants took part in the second listening test with additional stimuli, aged from 23 to 75, with a mean age of 38.3 and a standard deviation of 14.8.

Afterwards, correlations between the mean annoyance values and the acoustical - psychoacoustical quantities were then examined. Table 1 shows the crucial parameters with relatively strong correlation values with mean annoyance evaluations in both listening tests. Here, as expected, intensity parameters showed a substantial correlation with annoyance. Additionally, sharpness values demonstrated strong correlations, while the hearing model tonality showed moderate correlation strength. These parameters were selected as potential candidates for further modelling.

Table 1: Parameters with strong correlation with mean annoyance evaluations in both listening tests.

Pearson Correlation	dB(A)	Loudness ISO	Sharpness (Aures)	Sharpness (Bismarck)	Tonality (HM)
Listening Test 1	0.961**	0.977**	0.940**	0.719**	0.426*
Listening Test 2	0.966**	0.963**	0.763**	0.257*	0.439**

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

By examining the correlation between potential input parameters to mitigate multicollinearity and redundancy (Table 2), it is unsurprising to find a high correlation between the Aures sharpness model and loudness, given the nature of the Aures sharpness definition [2], which directly incorporates variations in loudness within the model. On the other hand, the Bismarck model [3] could be able to explain any annoyance variance, which cannot be directly explained by loudness variance, given the weaker multicollinearity. Lastly, in both listening experiments, no strong correlation between loudness and hearing model tonality was found. At the end, loudness, Bismarck sharpness and hearing model tonality were selected as possible candidates for further modelling.

Table 2: Correlation between potential input parameters

Pearson Correlation	Listening Test 1	Listening Test 2
Loudness and Aures Sharpness	0.944**	0.778**
Loudness and Bismarck Sharpness	0.710**	0.243*
Loudness and HM tonality	0.394*	0.492**

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

Annoyance vs. Tonality

The relationship between tonality and annoyance, while significant, was found to be moderate. This moderate correlation was rather unexpected, since it is a known fact that the tonality is one of the crucial factors decreasing the sound quality. This moderate effect could be a result of several factors: Firstly, our testing methodology inherently places greater emphasis on loudness and short-term memory, which may overshadow the influence of tonality. Secondly,

correlation analysis assumes a linear relationship between variables, which may not fully capture the specific nature of the relationship between tonality and annoyance in that case. A detailed investigation of the relationship between the tonality and annoyance revealed a more stepwise behavior (Figure 5), where many stimuli lack tonality, but those that do exhibit tonality were often perceived as highly annoying (red area). Therefore, while the effect of tonality on annoyance is strong, linear correlation values alone may not sufficient to accurately depict participant expression, emphasizing the complexity of this association.

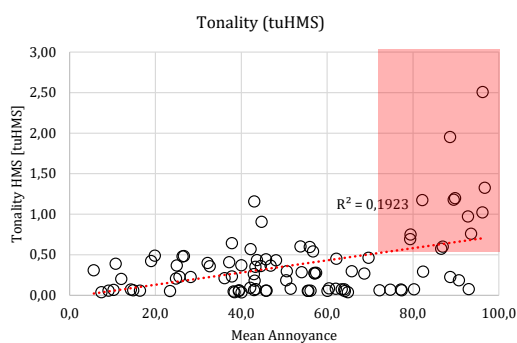


Figure 5: HM Tonality vs. Annoyance.

Furthermore, an examination of the frequency of tones present in the stimuli used revealed three distinct groups, defined as LOW, MID, and HIGH regions (Figure 6). The LOW region is a band around 100 Hz, explaining the commonly seen tones at this frequency amongst different vacuum cleaners. MID region was defined to describe tones up to 1000 Hz, knowing the fact that tonality perception has different features up to this frequency. Lastly, HIGH region includes tones occurring after 1000 Hz and above. Strong tonality values were observed in the HIGH region. Consequently, for further modeling steps, only this region was considered. If a signal contains more than one tone in this area, the tonality values of the stronger of these tones were used in the modeling.

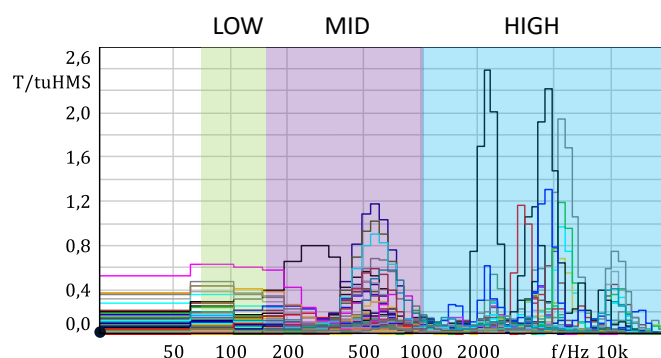


Figure 6: Tonality values according to the hearing model. Three distinct group of tones observed in the stimuli, defined as LOW, MID and HIGH. Low is the tones around 100 Hz, Mid is for the tones up to 1000 Hz and High for the tones above 1000 Hz.

Annoyance Model

It appears reasonable, therefore, to construct a multiple linear regression model based on the outcomes of the second

listening test, by using the variables of loudness, Bismarck sharpness, and high-frequency hearing model tonality, deduced from the experiments. However, in this constructed model, only the variable of loudness demonstrated statistical significance (Table 3). Moreover, upon attempting to construct three separate models sequentially, beginning with a model comprising solely the loudness variable and subsequently incorporating the sharpness and tonality variables in subsequent models, no particular improvement in model performance was observed with the inclusion of additional variables (Table 4). While these statistical findings were valid, they seem somewhat incongruent with intuitive, acoustical, and inferential considerations.

Table 3: Coefficients of a model using the loudness, Bismarck sharpness and high frequency hearing model tonality, obtained from the results of listening test 2

Input	Uns. β	Std. Error	Std. β	T	Sig.
Constant	0.020	5.095		0.004	0.997
Loudness ISO	2.727	0.094	0.957	28.933	<0.001
Sharpness Bismarck	2.346	2.993	0.023	0.784	0.435
Tonality-HIGH Hearing Model	0.071	1.987	0.001	0.036	0.972

Table 4: Model summary for each additional input parameter

Model*	R ²	Adjusted R ²	Standard Error
1	0.927	0.926	6.64
2	0.927	0.926	6.65
3	0.927	0.925	6.69

*1: Constant, Loudness ISO
 2: Constant, Loudness ISO, Sharpness Bismarck
 3: Constant, Loudness ISO, Sharpness Bismarck, Tonality-HIGH(HM)

Considering both the predominant influence of intensity parameters and the uneven distribution of dB(A) values within the specified range, it was expected that separate models could be established for different dB(A) ranges. The Figure 7 illustrates the relationship between dB(A) values and mean annoyance values for the second listening test. The mean value of all the dB(A) values calculated for all stimuli (approx. 62dB(A)) and a one standard deviation (approx.. 8 dB(A)) neighborhood of dB(A) values correspond to the range between 54 and 70 decibels, encompassing approximately 65% of the datasets utilized in the listening test. Additionally, approximately 16% of stimuli are located at lower dB(A) levels, while 19% are observed at higher levels. Particularly, samples at these three different sound level ranges do not exhibit uniform representation within the model. Therefore, different statistical models have been constructed for these three different levels of intensity. By employing a comparable step-by-step modeling approach, it was found that the inclusion of newly added terms enhances model performance, as defined by the adjusted R², within each defined region as shown in Table 5. Consequently, the model exhibits a relatively high determination coefficient in the other two regions, yet notably performs more effectively in the middle region, characterized by a higher density of stimuli.

In light of these observations, a piecewise continuous multiple linear model could be constructed, drawing from statistical inferences and acoustical deductions between the spectral features of the noise samples and participant feedback. The regression coefficients of the three used parameters for three different regions can be found in Table 6.

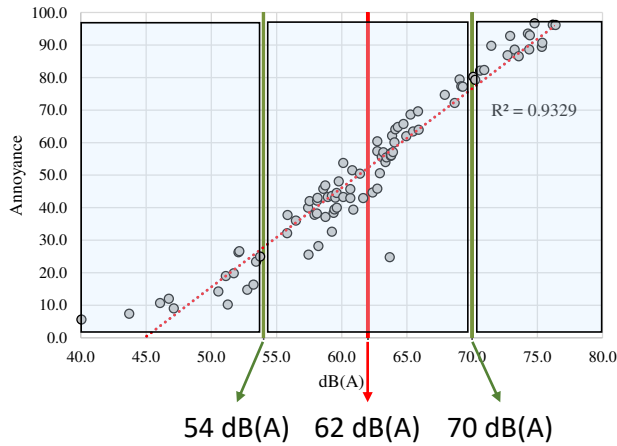


Figure 7: dB(A) vs. mean annoyance in Listening Test 2. The red line represents the mean dB(A) value among stimuli, while the green lines depict the one standard deviation neighborhood.

Table 5: Model summary for each additional input parameter within each defined dB(A) region.

Region	Model*	Adjusted R ²
Low <54 dB(A)	1	0.743
	2	0.771
	3	0.797
Mid 54-70 dB(A)	1	0.848
	2	0.860
	3	0.866
High > 70 dB(A)	1	0.762
	2	0.768
	3	0.785

*1: Constant, Loudness ISO
 2: Constant, Loudness ISO, Sharpness Bismarck
 3: Constant, Loudness ISO, Sharpness Bismarck, Tonality-HIGH(HM)

Table 6: Regression coefficients of the model within each defined dB(A) region

Region	Constant	Loudness ISO	Sharpness Bismarck	Tonality HIGH (HM)
Low <54 dB(A)	-12.98	3.076	3.229	17.979
Mid 54-70 dB(A)	-15.04	3.123	8.528	5.493
High > 70 dB(A)	41.83	1.235	3.238	1.549

The performance of this model can be compared to the performance of a model with only loudness. The relationship between loudness and annoyance in isolation (Figure 8) displayed an approximate S curve, but this was improved with the three-piece nature of the model (Figure 9).

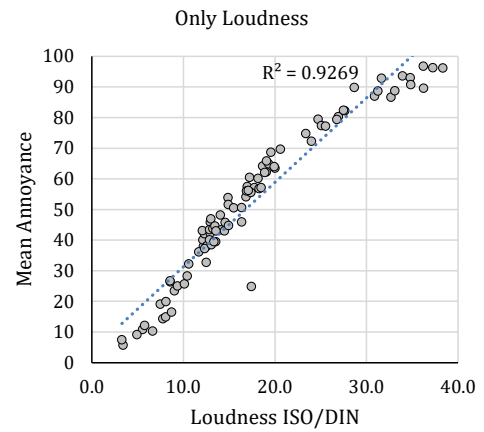


Figure 8: Loudness vs. annoyance.

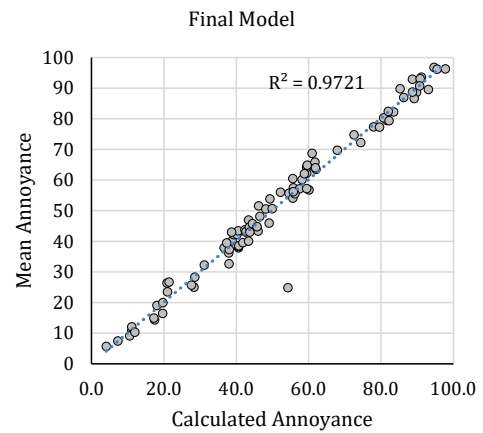


Figure 9: Calculated annoyance based on the developed model vs evaluated annoyance.

Like any statistical model, this model is not without limitations and is subject to error, re-evaluation, and improvement. The primary objective here is to pragmatically enhance the usability of parameters incorporating the effect of spectral features on annoyance, beyond the overall level. Manufacturers can utilize such a model for A-B comparison, thus identifying problematic devices and design aspects, and subsequently formulating solutions.

References

- [1] Household and similar electrical appliances - Test code for the determination of airborne acoustical noise - Part 2-1: Particular requirements for dry vacuum cleaners
- [2] Aures, Wilhelm. "Berechnungsverfahren für den sensorischen Wohlklang beliebiger Schallsignale." Acta Acustica united with Acustica 59.2 (1985): 130-141.
- [3] von Bismarck, Gottfried. "Sharpness as an attribute of the timbre of steady sounds." Acta Acustica united with Acustica 30.3 (1974): 159-172.