

Towards an European Sound Label for Household Appliances: Psychoacoustical Aspects and Challenges

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Abstract

The European Union energy label, which provides information on the energy consumption of household appliances, has proven its reliability for the customers in recent years. However, a label for the product sound perception, which can be very useful for the customers but also manufacturers, is not available up to now. The energy label is required to include the sound power level of the devices. Although the sound power level is an important acoustical parameter, it does not characterize the customers' perception of product sound sufficiently. The psychoacoustical parameters, e.g., loudness, sharpness, tonality, roughness, fluctuation strength, etc., are much more useful for characterization purposes. However, in some cases it is required to adapt these parameters for complex household product sounds and to model their interaction. Another important issue refers to the optimal measurement environment (anechoic chamber vs. real living environment) and the measurement conditions for sound quality testing. The aims of this study are to summarize the results of investigations, which were conducted on two different household appliances (vacuum cleaner, dishwasher), and discuss the future milestones on the way to a European sound label.

Index Terms: sound quality, household appliances, annoyance, sound label, psychoacoustical metrics

1. Introduction

Household appliances have become an important part of our daily life. Their operating noises can positively or negatively influence our life quality. During the usage of these products, in some cases visual, auditory or tactile feedbacks provide sufficient information to the user regarding the operational condition or the safe usage. In these cases, the feedbacks are necessary for an optimal user-product interaction. However, we don't have any need to hear permanently the sound of the refrigerator in order to know that it functions. If we want to sleep or perform daily activities, we don't want to be disturbed from vacuum cleaner, refrigerator, or dishwasher noises.

When shopping, mostly it is not possible to listen to the machine in operation. Therefore customers consider the sound power level of the household appliance provided by the manufacturers. However, sound pressure or power level do not characterize the customers' perception of product sound. Although two different products may have same sound power level, the disturbance of the noises may vary. Additionally, customers seem to have considerable difficulties to assign meaning with dB values. Therefore, a sound label for household appliances, which represents the perception, would be very

useful for customers and manufacturers. It helps to improve life quality by affecting the competition between products.

The EU energy label, which is compulsory for white goods and based on the EU Directive 92/75/EC, is required to include the sound power level of the devices. Apart from that, there are several international and national ecolabels. For example the Blue Angel from Germany, the NF Environnement ecolabel from France or the TCO label from Sweden. Most of these labels define the upper limits for the sound power level of the products (a detailed overview can be found in [1]). Currently, there isn't any established national or international sound label, which attempts to characterize the customers' annoyance perception of product sound. Therefore, in this study, various investigations were conducted on the sounds of household appliances. In the first part of the study, fourteen vacuum cleaners from different brands were selected to evaluate the annoyance of the vacuum cleaner sounds. One fundamental issue of the prospective sound labeling is the measurement setup. Consequently, in the specification phase the first question to answer is: Which (omnidirectional microphone or artificial head) and how many sensors are required for the labeling measurement? Based on the answers given posing the following questions: where to place the sensors? and where is the optimal measurement environment? During the investigation, these questions were taken into account. The vacuum cleaner sounds have almost stationary character. Therefore a further investigation was conducted on dishwasher to evaluate the instationary product sounds.

2. Investigation on vacuum cleaner sounds

Vacuum cleaner is one of the widely used household appliances and they usually generate annoying sound. The four most common sources of vacuum cleaner noise are the motor, the fan, the airflow and the surface vibrations of the housing [2]. There are various types of vacuum cleaners, such as bagged, bagless, canister, upright, wet and dry, handheld, robotic, etc. In this study, we focused on bagged canister type vacuum cleaners. Altinsoy et al. [3], Ih et al. [4] and Róbert et al. [5] investigated the perceptual aspects of the vacuum cleaner sounds. All these investigations showed that sound pressure level is not sufficient to characterize the perception of vacuum cleaner sounds. Loudness, sharpness and roughness play an important role on the annoyance judgments.

Vacuum cleaners of various brands and with several different motors were selected for this investigation. One of the important selection criteria was that the stimuli should represent wide character variety of the vacuum cleaner sounds. The sounds of fourteen vacuum cleaners were binaurally (using the artificial head Kemar) and monaurally (using an omnidirectional microphone of Brüel & Kjær) recorded. The vacuum cleaners were placed on the floor with carpet. The handle was in upright

position. The position of the microphone and the artificial head were selected based on the common user position. The handle and brush were at the front and the vacuum cleaner was at the back. The height of the microphone was 1.65 meter above ground. The vacuum cleaners run at the highest level. The recording setup is shown in Figure 1.

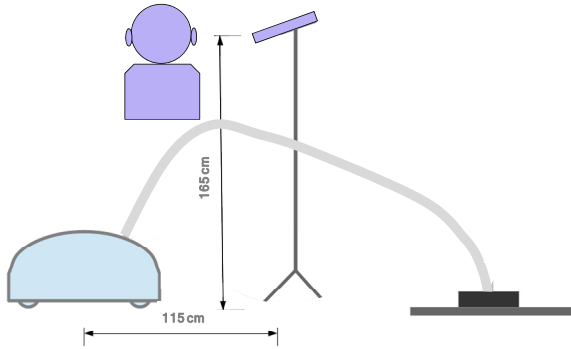


Figure 1: Setup for recording vacuum cleaner sounds.

2.1. Subjects

Twenty-two subjects, twelve men and ten women aged between twenty and fifty-five years, participated in the experiment. The subjects had no specific knowledge regarding acoustics or vibrations. All of the subjects exhibited normal hearing (tested) and were paid for their participation on an hourly basis.

2.2. Listening test setup and procedure

The recorded sounds of the 14 vacuum cleaners were presented to the subjects through HEAD acoustics HA II.1 headphones using a PEQ IV equaliser. The presentation sound level was calibrated. The experiments were conducted in a sound-attenuating room.

In the training phase, all of the participants were presented with different combinations of stimuli from across the full stimulus range, and they were then familiarized with the procedure of the experiment. Subjects were asked to evaluate the annoyance of the vacuum cleaner sounds. A Matlab graphical user interface was used for the experiment. The subjects indicated the intensity of their associations on a continuous 100-point unnumbered graphical scale, which was marked with verbal anchors describing different intensities (not at all, slightly, moderately, very, extremely) [6]. Stimuli were presented in random order.

2.3. Stimuli

The short-time Fourier transform (STFT)-based spectrograms of fourteen vacuum cleaner sounds are presented in Figure 2. The spectrograms were obtained with 4,096 FFT points.

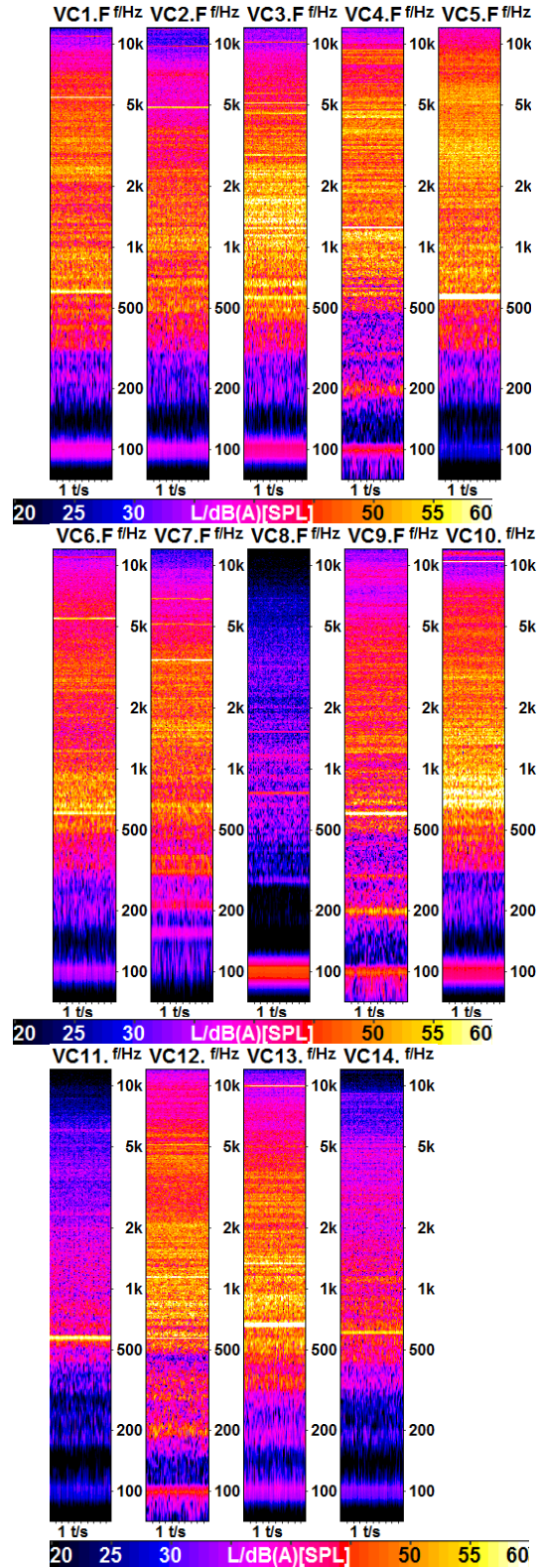


Figure 2: The STFT-based spectrograms of vacuum cleaner sounds.

The level range of the vacuum cleaner sounds vary extremely. In the majority of the spectrograms, the presence of tonal components can be observed. These components are mainly caused by motor (supply frequency, rotation speed and pole number-dependent) or fan (rotation speed and blade number dependent). The prominence and the incidence of the tonal components vary between sounds. Some vacuum cleaner sounds have strong 100 Hz frequency component (for example VC4, VC8, VC12, etc.). The spectrogram of some vacuum cleaner sounds show intensive high frequency content (for example VC4, VC5, VC10, etc.).

2.4. Results and Discussion

The annoyance judgments were averaged across the 22 subjects for both recording methods and are shown in Figure 3 with the sound samples (along the abscissa) being arranged in ascending order according to the mean annoyance produced by the vacuum cleaner sounds. The results show that the annoyance order of the vacuum cleaner sounds are same in both cases and the ratings do not differ from each other significantly. It is possible to say that although artificial head has some advantages for product sound recordings (such as correct localization, etc.), diffuse-field measurement microphones can also be used.

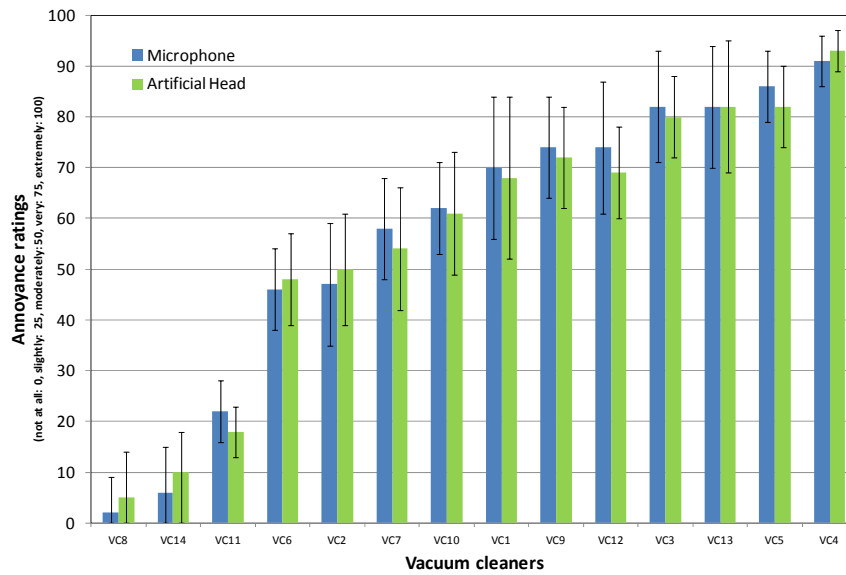


Figure 3: Annoyance ratings of the vacuum cleaner sounds.

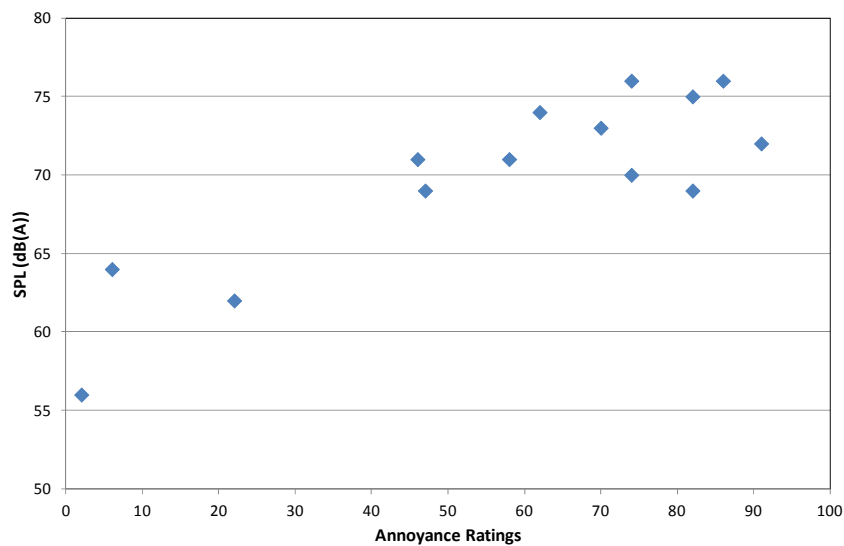


Figure 4: Results of regression analyses between the annoyance judgments and SPLs in dB(A).

The comparison between the sound pressure level (SPL) and annoyance ratings of vacuum cleaner sounds revealed that there is no simple linear description of this relationship (Figure 4). A regression analysis between SPL in dB(A) and the annoyance ratings for the 14 vacuum cleaner sounds resulted in correlation coefficient of $r^2 = 0.7$.

Not only intensity related terms but also other signal-based attributes in terms of spectral and temporal properties play important roles in the perception of vacuum cleaner sounds. The results of the investigation show that tonal components at high frequencies have high weight in the judgments as they cause annoyance. Apart from that very loud vacuum cleaner sounds also cause annoyance. The rattling at power supply frequency and its harmonics also causes annoyance. Modulation in vacuum cleaner sound captures our attention and is undesirable. The coefficient of determination scores can be improved using the psychoacoustical parameters such as loudness, sharpness (which is important in characterising the influence of high frequencies), roughness (which is important in characterizing the modulation related perceptions), and tonality. An index was developed to account for the relationship between the annoyance ratings and the calculated psychoacoustic parameters. In this study, the Zwicker model was used for the calculation of the loudness (ISO532B), the Aures models were used for the calculation of sharpness and roughness [7, 8], the Aures/Terhardt model was used for the calculation of the tonality [9, 10]. An interview was conducted after the experiment. In this interview, it was noticed that most of the subjects claim that it is very annoying, when vacuum cleaner sound disturbs their communication with partners or other residents. Similarly, they are annoyed, when vacuum cleaner sound disturbs television watching or phone call. Therefore the intelligibility of speech, which can be predicted using the articulation index (AI) or speech intelligibility index (SII), is an important threshold for pleasantness. In this investigation, the articulation index was used for the index calculation and determined that 65% AI is an important threshold. If the AI is higher than 65%, the role of the loudness on the annoyance judgments is almost negligible. If the loudness of the vacuum cleaner sound is higher than 35 sone, the loudness dominates the annoyance judgments. A comparison of the psychoacoustic parameters of the vacuum cleaner sounds and their annoyance ratings showed that loudness and sharpness are almost equally important for the quality judgments. Although the roughness and the tonality play an important role on the evaluation, their importance is not as great as the loudness and sharpness parameters. Considering the differences in the numerical values of the loudness, the sharpness, the roughness, and the tonality, the weightings of the psychoacoustical parameters were determined and the index was defined using the following formula:

$$\text{Index} = L + 6*S + 15*T + 10*R + ((100 - \text{AI})/8)$$

where L is the loudness, S is the sharpness, T is the tonality, and R is the roughness. A regression analysis between the developed index and annoyance ratings resulted in a correlation coefficient of $r^2 = 0.92$ (Figure 5). It was noticed that, in some cases the results of the roughness and tonality models differ strongly from the perceptual roughness or tonality judgments. Similar problems were observed with other existing models [11, 12]. To achieve a better correlation, an adaptation of the existing

roughness models (Aures, Daniel and Weber or Sottek, etc.) or tonality models for the vacuum cleaner sounds may be useful.

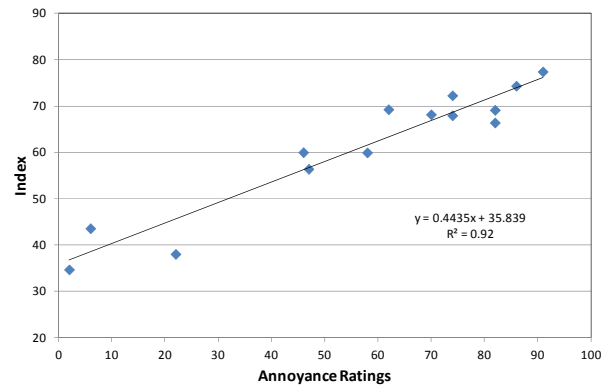


Figure 5: Results of regression analyses between the annoyance judgments and the weighted combinations of the psychoacoustic properties.

3. Investigation on dishwasher sounds

The vacuum cleaner sounds have almost stationary character. Therefore a further investigation was conducted on dishwasher to discuss the challenges in the development of a sound label for the instationary product sounds. Therefore in this section we will concentrate on the relationship between the instationary character of dishwasher sounds and their perception, rather than to report the details of the investigation and the label.

Typical sound sources of a dishwasher are pump (circulation/drain), motor, spray arms, water sloshing (impact excitation), water flow, water-inlet valve, heating and drying fan. Before starting the wash cycle, the dishwasher takes cold water from the water supply, warms it up and the warm water is forced through the spray arms by the electric pump. In the wash cycle, while the dishwasher is running, the spray arms splash the water up against the dishes/plates, the inside of the tub and door, as well as the water moves around inside the dishwasher. During the wash cycle, the detergent cup opens automatically. After each wash cycle, the dishwasher drains the dirty water. Rinse and drain cycles are repeated several times. At the end the dishwasher heats the air to dry the dishes. All these processes cause various characteristic sounds, which differ from each other.

Six dishwashers of various brands were selected for this investigation. The sounds of dishwashers were recorded using a omnidirectional microphone of Brüel & Kjær. The analysis of the sounds showed that the sounds of the above mentioned processes should be evaluated first individually and then as complete course. In the first investigation (20 subjects, 10 men and 10 women), the procedure was the same as the vacuum cleaner investigation and participants evaluated the annoyance of the sounds for each individual process (duration 5 second). In the second investigation (4 subjects, 2 men and 2 women), participants read a book or a magazine, while the whole dishwashing process sound (duration is approximately 90 minutes per stimulus, altogether 6 stimuli) was played back. After all, an interview was conducted and participants reported if there are annoying sequences or which sequence was the most annoying.

It is possible to explain the typical characteristics of these individual processes using the STFT-analysis of a dishwasher sound (Figure 6). Figure 6a shows the process “dishwasher takes cold water and warms it up”. It begins with a broad-band impulsive sound and continues with 100 Hz and other tonal components. An example course of the wash cycle was shown in Figure 6b and three selected time courses of this wash cycle were zoomed and shown in Figure . The level differences between the

time sequences 1, 2, and 3 are observable and perceptible. However there is not a big timbre difference between the time sequences. Figure 6f shows the drain process. At the beginning of the process, there is a noticeable level increase. There are strong tonal components at 100 Hz and 400 Hz similar to other process sounds. However, temporal sound character is noticeably different from the wash cycle.

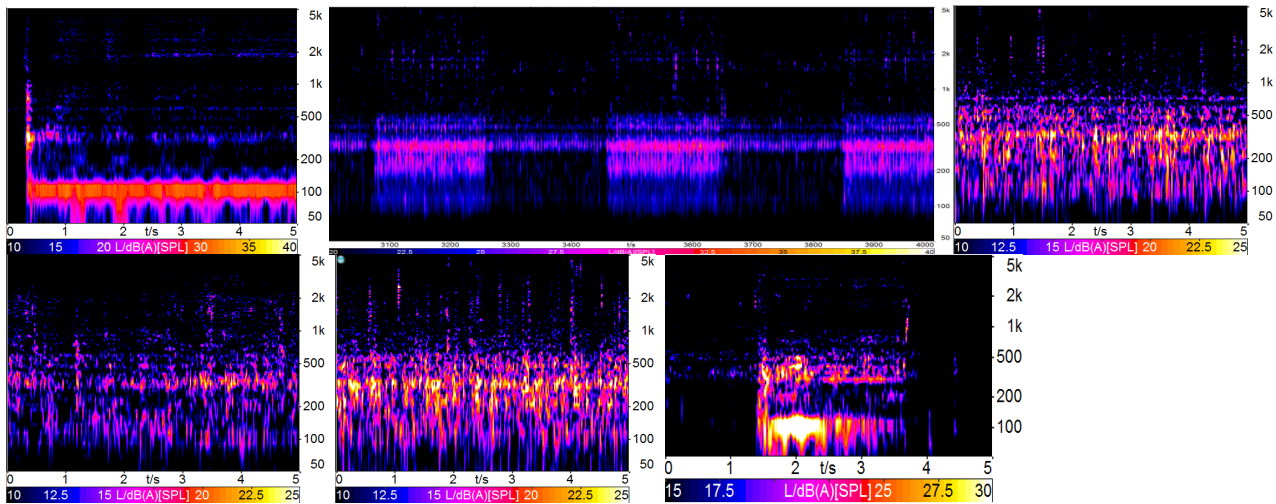


Figure 6: The STFT-based spectrograms of dishwasher sounds.

In the interview, the participants reported that although in some stimuli, pumping sounds evoked low quality feeling, their contribution to the overall annoyance was negligible. They also reported that during the wash cycle temporal changes of the sound cause very much annoyance.

Sound label considers only the annoyance of the sound but not the overall perceived quality of the sound. The comments of the participants and annoyance judgments revealed that in the calculation of the sound label, it is possible to use average values of the psychoacoustic metrics over time. Although the extreme but short (in comparison to whole operating cycle) events can play very important role on the perceived quality or dominate our quality experience, in dishwasher sound case, they don't dominate the overall perceived annoyance.

4. Discussion and Challenges

In the first part of this study, the annoyance of the vacuum cleaner sounds was evaluated. The results show that psychoacoustic metrics such as loudness, sharpness, tonality and roughness play an important role on the annoyance perception of the vacuum cleaner sounds. This observation is in line with the previous studies [3,4,5]. Furthermore the speech intelligibility, which can be described using the articulation index, is an important factor for the modeling the annoyance of the household appliance sounds. Most of existing psychoacoustic metrics are based on classical psychoacoustical test signals (such as sinusoidal tones, white or pink noises, amplitude modulated tones, etc.), therefore an adaptation of these metrics for the complex household appliance sounds is necessary to achieve greater consistency between the labels and the perceived annoyance. To ensure the comparability of the vacuum cleaner

sounds, the suction power of the machine should be taken into account as parameter.

In the second part of this study, the annoyance of the dishwasher sounds was evaluated. The operating cycle of a dishwasher consists of various distinctive steps and highly instationary. Recently, different studies have focused on the loudness perception and evaluation of instationary sounds [13,...20]. While the results of some investigations show that the global loudness judgment of a time variant signal is the simple average of the continuous judgments, other studies claim that it is not a simple average. In this study the results revealed that it is possible to use average values of the psychoacoustic metrics over time to estimate the overall annoyance of the dishwasher sounds. This result is only valid for the estimation of the overall annoyance of dishwasher sounds, but not for the overall quality perception. The investigations, which were conducted in this study, should be extended for other instationary household appliance sounds. One important issue is that in some cases there are differences regarding the evaluation of the household appliance sounds in laboratory and field [21, 22]. In this study, we tried to take into account this issue in the evaluation of the dishwasher sounds.

In this study, the discussed sound labels for both household appliances don't take into account the semiotics and meaning of the sounds [23, 24, 25, 26]. But it was also not our aim. The consideration of these aspects may require much more complex modeling. One important observation in this study was that the standard deviation of the annoyance ratings was not very high and there were not distinctive user groups who follow different judgment strategies.

5. Acknowledgements

The author wish to thank the Eureka (Project 8684: Sound Quality of Household Appliances for Life Quality) for supporting this work.

6. References

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