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Product Sound Quality and Sleep Disturbance

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ABSTRACT
Products operating inside residential spaces present sound level and sound quality requirements. These requirements for daytime operation depend on their function, their interaction with the user(s), the level of background noise and the users' expectation. The process to derive their sound quality target is well established and guidelines can be easily found in literature. When these products operate also at nighttime, the sound quality concern turns into a multifaceted sleep disturbance concern: the noise generated should not impede the users' ability to fall asleep and should not cause them to awaken. While sleep disturbance caused by exterior noise sources as traffic and industrial premises has received a significant attention from researchers and legislators, little is known about sleep disturbance from interior sources such as medical devices (respiratory support, dialysis, etc.), air conditioning and air recirculation systems, automatic deodorizer dispensers, etc.. This paper will describe the approach followed by the authors to develop sound quality and sleep disturbance targets for consumer products that may operate both at day and night time. The noise generated by an automated dialysis machine and by an automatic air freshener dispenser will be analyzed and preliminary sound quality and sleep disturbance targets will be derived.

1. INTRODUCTION
The Sound Quality of home appliances (from refrigerators, to vacuum cleaners and sewing machines among others) has long been a product differentiator and manufacturers have been using sound quality metrics along with sound power to evaluate their products[1,2,3]. In more recent years, manufacturers of other various home products, typically powered by small electrical motors, have also started to be concerned with noise level and sound quality. A couple of examples are automated window shades and automated air freshener dispensers. In regard to the window shades, they are expected to make some noise, but this has to be smooth and continuous during the shade motion, with little or no discontinuity and no perceivable "wow-wow" (modulation) and whine type of noise. This is a sound quality issue; the product is expected to produce noise which matches the user's expectation.

The automated air freshener dispensers present a more complex challenge to the engineering team. Of course, they are expected to be quiet during operation (a quick release, i.e.

2-3 seconds, of air freshener produced by either a pump or an aerosol can). In addition, if the automated air freshener dispenses at night, its noise should not cause people to awaken. This is a sleep disturbance issue. Noise targets to avoid sleep disturbance from external sources (traffic and industrial complexes) have been established by the World Health Organization (WHO) and local governments and institutions but little has been published regarding sleep disturbance from in-home consumer products [4,5].

An even more complex noise control engineering problem is posed by medical equipment, especially for home use. Equipment for medical research laboratories and for hospitals have the SQ criteria to be quiet and not annoying to guarantee good speech intelligibility and less fatigue for patients and staff. As an example, an ultra centrifuge, used in medical labs to separate substances at a molecular level, spins the vials at very high angular velocity (50,000 RPM and higher) continuously for several hours. When you consider that there may be several centrifuges running simultaneously in an open space environment where researchers also work, it is clear that noise and sound quality are important product differentiators for this type of equipment. The same situation occurs in hospitals, especially in areas with a high concentration of equipment per patient, such as ICU's. In recent years, with the aging of Baby Boomers and increasing hospital stay costs, home care products have become more readily available. Examples among others are ventilators, used for machine-assisted breathing, and automated dialysis machines used for end-stage renal disease treatment. Since these machines typically have to function also at night, it is important that they do not impede the patient's ability to fall asleep and should not cause him/her to awaken. The SQ requirement in this case for the product is annoyance and sleep disturbance.

The section below presents a review of published information on sound quality, annoyance and sleep disturbance. These data were used by the authors as guideline during the noise investigation of an automated air freshener dispenser and an automated peritoneal dialysis machine. Next, details from each of these investigation will be discussed, along with the final results and recommendations from the authors.

2. REVIEW OF SOUND QUALITY, ANNOYANCE AND SLEEP DISTURBANCE

A. Sound Quality and Annoyance

Sound Quality defines the perception of the noise of a product. As such is defined by two ingredients: the absolute noise of the product (i.e. sound power) and its perception from the user (psychoacoustic), as simply depicted in Figure 1. Sound Quality is multi-dimensional, that is the perception is affected by multiple dimensions (or characteristics) of the sound. The process to evaluate the sound quality of a product and to establish a sound quality target is shown in Figure 2. More details on sound quality terminology and process can be found in references [6,7]. .

Figure 1: What Is Sound Quality?

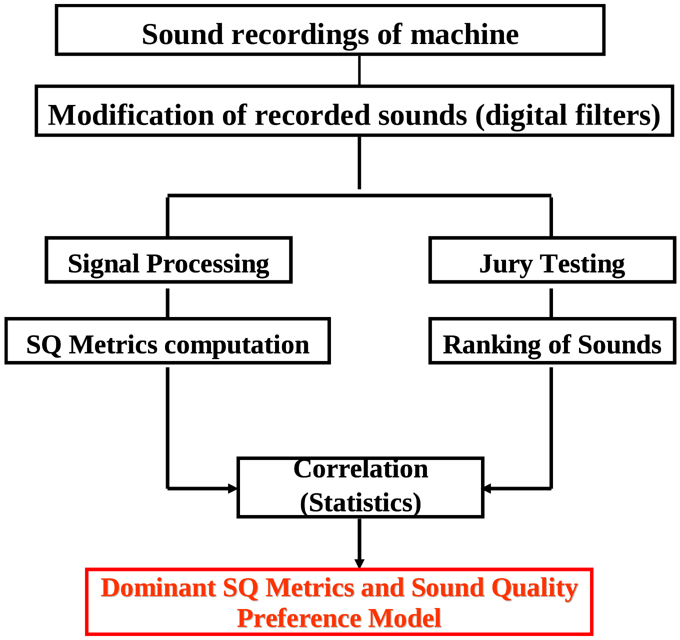

Figure 2: Sound Quality Evaluation Process

With the jury test, the opinion of a group of people is gathered. This is then correlated to objective parameters (sound quality metrics) derived from the same sounds judged from the jury. From the correlation process, the main dimensions of the sounds which drive the opinion of the jurors are established. Next, the best metric to describe each dimension are derived. This allows to develop a Sound Quality Preference model that can be used to drive product design and development.

For an appliance/home care product, there are several sound quality aspects that need to be evaluated and measured:

- Passive Sounds. In this case, Sound Quality of the user's interaction. These are the sounds that the unit makes when it is touched but it is not operating (opening/closing panels, pushing buttons, etc.). Depending on the user sensitivity to noise, they may affect the purchasing decision.
- Running/Operating Sounds. This is the sound that the machine makes when operating. The noise in this case does not need to convey any information; it needs to be low and not annoying.
- Action Sounds. These are the sounds the machine makes when switching from one operating mode to another. This could be the end of the washing cycle in a washing machine or the change from pulling vacuum to pressurizing the lines in a blood transfusion machine. These sounds do not necessarily need to convey information, so the transition has to be minimized.
- Signal Sounds. These are also called "chimes" and are designed to provide information to the user. They can be rather simple (as in a dishwashing machine to signal the end of the cycle or in a car to signal the driver that the door is not properly closed) or need to be designed to carry multiple information, such as warning signals in a peritoneal dialysis machine.

The relationship between sound quality, annoyance and sleep disturbance may be intuitively clear but it is difficult to define. Considerable research has been done on the subject of annoyance and its relation to loudness, noisiness and sound quality in general.

Loudness is the most important dimension (or component) of the sound, and it is defined as the subjective intensity of the sound independent of any meaning the sound might have[8] Sound Quality is multi-dimensional in the sense that more dimensions, other than loudness, affect the perception of acoustic quality. Taking it one step further, annoyance is affected not just by sound quality but also by non-acoustic factors, as described in references [9,10,11]. These non-acoustic factors, such as relation to source, personality, meaning of sound, situation, time of day or day of the week, and others, may affect annoyance more than the physical parameters (frequency and time) of the sound. The most extreme aspect of annoyance is sleep disturbance, meant as both the impediment to falling asleep and the awakening due to noise. Investigations of sleep disturbance are very difficult since if they are done at home, a large number of subjects is required due to the uncontrolled conditions of the test. If they are done in a lab, test subjects experience an environment which is quite different from their own. In the next section we provide a brief review of literature on sleep disturbance.

B. Sleep Disturbance

When confronted with the task of judging the sound of a product with regard to sleep disturbance, the authors (none of whom being a psychoacoustician) first reviewed the literature to gather background information on sleep disturbance. While a lot of material on sleep disturbance from external sources (traffic and industrial) is available, very little was found in relation to the disturbance from interior sources. This was the case for the air freshener and for peritoneal dialysis machine presented in this paper. The findings of the literature research can be summarized as follows:

- WHO guidelines say that for good sleep, sound level should not exceed 30 dB(A) for continuous background noise, and individual noise events exceeding 45 dB(A) should be avoided.
- Recent findings, however, provided strong evidence that noise starts to induce arousals at LAMax values in the range 30-35 dB(A) (probability of arousals depending on age, gender, job, and several other factors).
- No guidelines specific to domestic noise (i.e. created by interior sources) could be found, therefore the recommendation from WHO were used as a starting point.
- From a recent investigation carried out by researchers from Johns Hopkins Hospital in Baltimore regarding the noise level in several hospital areas, it emerges that in all areas, the noise level far exceeds (by 15-20 dB) the noise guidelines established by WHO for hospitals[12]. There is also evidence that the average noise levels in hospital has been increasing over the last years due to the increased number of machines used for monitoring and diagnosing patients' status, use of PA etc.. This may have a negative effect on patients (stress, fatigue, interrupted rest) and on medical/nursing staff as well.

The concerns for the home appliances are a) that their noise is not too annoying and does not impede people to fall asleep and b) that their noise does not cause arousals from night sleep. While the first concern is addressed by ensuring that the product noise is low and pleasant enough (using traditional sound quality approaches), the second has to do with the occurrence of significant changes of the noise. The following section describes how the authors have addressed these issues for a couple of different home products.

3. APPLICATIONS

A. Sound Quality: Automated Peritoneal Dialysis Machine

This type of machine is portable and follows the patient, therefore when the patient is in bed, the machine, roughly of the size of a microwave oven, is on a nearby table. According to a predefined therapy cycle, the machine delivers several medications to the patient through a network of tubing. Noise sources for this (and similar type of medical equipment) may include small compressors, centrifuges, heating, valving, and air circulation elements. During normal operating condition, the noise generated is intermittent, depending on the running mode of the compressors (vacuum or pressure), on opening/closing of valves to deliver medication and whether fans or centrifuges are operating. The objective of this study was to assess how different machines compare from a sound quality standpoint, understand which noise was found by the patients to be less annoying, and to establish sound quality guidelines to be taken into account by the engineering team when improving a production model or designing a new generation of models.

Recordings were made of different models from different manufacturers which were then edited and presented to a jury of approximately 70 people, of which a significant portion were patients. The sound quality jury study was part of a larger marketing effort organized by a major manufacturer of automated peritoneal dialysis machines to understand customers' needs and expectations. The sounds were presented according to a Paired Comparison scheme and the patients (jurors) were asked to identify the sound they preferred among the two in each pair. Along with the recorded sounds, additional sounds were created by enhancing or reducing specific features of the measured sounds. This was done to ensure more control on the variables as well as to test some preference hypotheses formulated by the sound engineers.

Figures 3a), b) and c) show the Loudness function versus time for three sounds with poor (a) , better (b) and best (c) score according to the jury. It can be clearly seen that while the running (background) noises are very similar, the worst sound (among the three) exhibits much higher peaks in loudness. These peaks are mainly due to valves opening/closing and other noises associated to the pneumatic system. Therefore a combination of absolute loudness measure and a ratio of percentile loudness values (such as N10/N90, as an example) may be used to capture both the overall impression of loudness as well as the impulsiveness of the transient events (i.e. the amount of the level difference between peak and background noise).

Figure 4 depicts another important dimension of the sound, the tonality of the noise. The data plotted on the left are loudness versus time (top) and FFT (bottom) of a sound that scored better than the sound on the right hand side (for which loudness is shown on top and FFT at bottom). Of interest is the fact that the sound on the left ranked better even though it is about 30% louder than the sound on the right. The reason is the presence of unmasked tonal components in the worse sound, while the tonal components are masked by higher background noise in the sound judged better. In other words, if tones cannot be avoided and attenuated, their perception can be greatly reduced by increasing the level of the masking. Naturally this masking strategy can be successfully applied only when it does not increase significantly the total loudness of the product, since loudness is the dimension that dominates perception.

The overall result of the jury study was that loudness, impulsiveness and tonality were the dimensions that most affected the perception of the sound of the automated peritoneal dialysis machine. Countermeasures to reduce the impact of these three characteristics were identified, mocked up and sound tested to identify their effectiveness.

Sleep disturbance was not investigated for this application.

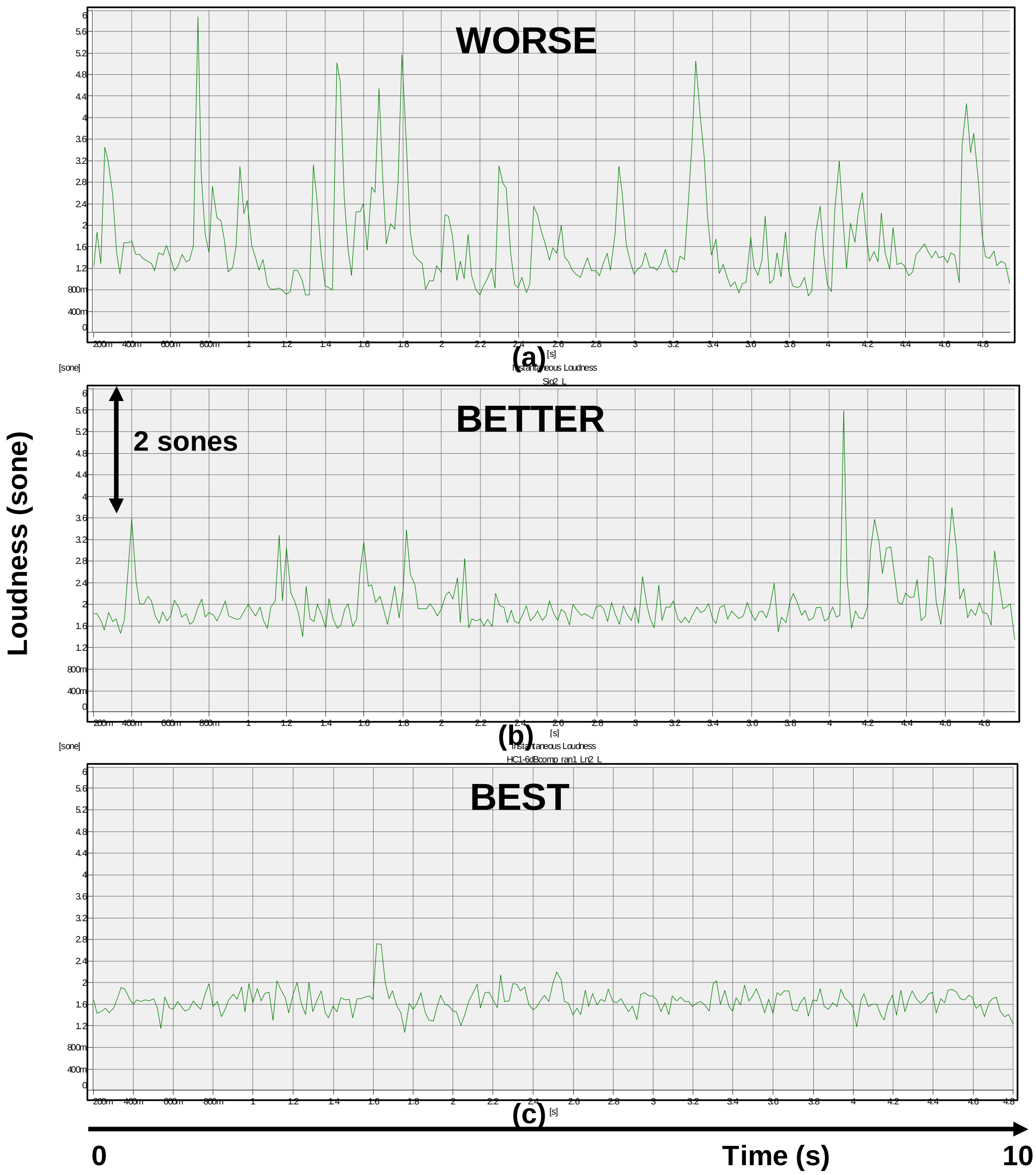

Figure 3: Loudness Function vs. time for three recordings of peritoneal dialysis machine (same scale)

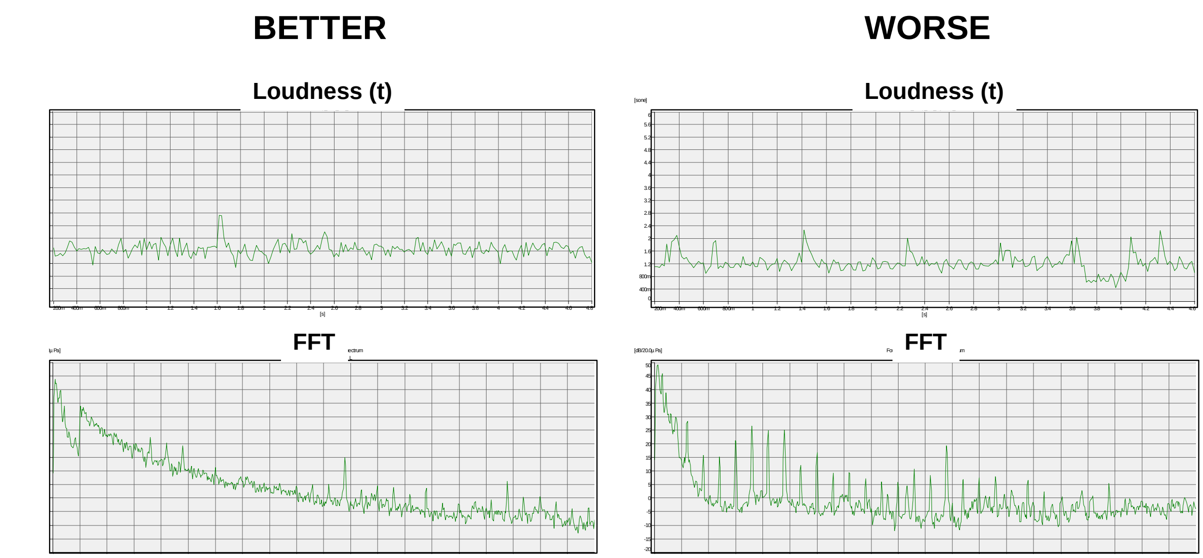

Figure 4: Loudness Function vs. time (top) and FFT (bottom) of better (left) and worse (right) sounding dialysis machines.

B. Sleep Disturbance: Automated Air Freshener Dispenser

Even an air freshener dispenser may present a sleep disturbance challenge. In this case, the authors needed to assess the probability that the sound of an air freshener could cause sleep disturbance, i.e. awaken people in the same room where the air freshener is installed or in an adjacent room such as a bathroom. Two types of air freshener were investigated: pump and aerosol can. The pump style freshener generates a noise which is typical of DC-motor powered mechanisms, with modulated whining (also called “wow-wow”). The aerosol can release mechanism is a transient, spring loading-unloading type of noise. Figure 5 shows Loudness function vs time for two air fresheners of different types: aerosol can on the left and DC-motor powered pump on the right.

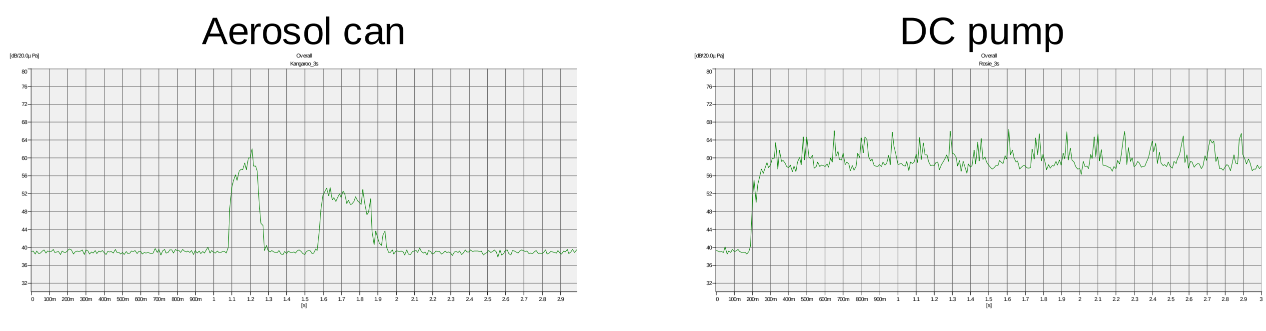

Figure 5: dB(A) Function vs. time for two types of air freshener dispenser

From a sleep disturbance standpoint, the amount of change of noise is the dominant factor, therefore the best type is the aerosol can because of its smaller level increase from background noise in the bedroom to dispensing action. It is difficult, however, to directly evaluate whether this air freshener dispenser would cause arousal from sleep since these measurements were taken in a hemi-anechoic chamber at 1m from the unit. The WHO requirement is for less than 10 dB increase at the receiver location. Therefore this particular aerosol can type unit could be acceptable if placed farther than 1m from a sleeping person. This suggests that a measure of sound power and limits on sound power (derived from threshold of annoyance at receiver position) would be more useful for this type of product than sound pressure measurements.

4. CONCLUSIONS

Annoyance and Sleep disturbance concerns have to be considered separately than sound quality. The main discriminating factor for sounds in relation to sleep disturbance is the relation of the events level to the background noise level. Based on the products evaluated and taking into account published sleep disturbance information, the following is recommended as a means to set level difference targets for sleep disturbance:

- Transient Sounds
    - N10 / N90 where Nx is the Loudness exceeded by X% of the data points in the recording. Therefore N10 is a close (but conservative) approximation of the maximum loudness and N90 of background noise. Or
    - L10 – L90 (dB) is the difference between A-weighted SPL of event and background
    - i.e. N10 / N90 < 3 or L10 – L90 < 10dB
    - Note: Statistical descriptors depend on the total number of data points, i.e. require a "normalized" time window around the event.
- Constant Sounds
    - Difference between Average Loudness (or dB(A)) during the event and average background noise before event started.
    - i.e. Maximum level increase (above background) < 15 dB

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