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Acoustic comfort of air-treatment systems: influence of factors related to room acoustics

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Summary
This study aims at defining reliable acoustic cues for the measure, characterization and prediction of the acoustic comfort of air-treatment systems (ATS). To meet customers' expectations, industrial products tend increasingly to follow a process of "sound design". In this process, the perceptual evaluation of sound quality is a necessary step to define acoustic specifications. Nonetheless, the possible influence of factors related to room acoustics is often neglected. Contextual parameters, such as room acoustics' factors, should be integrated in the evaluation of sound quality in order to define acoustic comfort as it is perceived in a real environment. First, a sound corpus of a reasonable size was constituted through a categorization experiment over a large recording database of different types of ATS. Then, an experiment was conducted to build a scale of acoustic comfort over the sound corpus and relevant acoustic features for prediction were identified. Two different situations were considered: diotic presentation and auralized presentation (using a 3D vector base amplitude panning system), the results of which were finally compared in order to address the relative importance of room acoustics' factors for the judgement of the acoustic comfort of ATS.

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1. Introduction

Sound quality evaluation has been an issue of great interest in many studies, due to important applications in the industrial world. Indeed, acoustics is nowadays of significant importance for companies because consumers' choice criteria include, among other things, the acoustic comfort associated with the product, that is, the ATS in the present purpose. In order to differentiate themselves from competitors, manufacturers are now inclined to follow a process of "sound design" [1] in which the evaluation of acoustic comfort is a critical step in defining the acoustic specifications of the product. Thus, they try to define to which extent perceptual parameters affect the annoying, intrusive or unpleasant character of the sound produced by an object designed for a particular function and not specifically created to have a "nice" sound, unlike musical instruments for example.

Many studies addressing sound quality evaluation are found in the literature. Different experimental methodologies are adopted depending on the context of each study and the type of product under consideration. Two steps are involved: first defining the main auditory attributes for the perception, then identifying a continuous unidimensional scale of sound quality. The results are specific to the category of sounds under study. However, the sounds are often based on anechoic recordings, and environmental cues are removed. This particular condition of recording differ strongly from actual hearing conditions.

The present work is part of an ongoing study addressing the effect of factors related to room acoustics on the measured acoustic comfort of ATS. More specifically, two different conditions of acoustic comfort will be compared, the first involving anechoic recordings and the second sounds processed by an auralization program to take into account more realistic environments. First, in Section 2 a representative ATS sound dataset of reasonable size is defined through a free-sorting experiment. Then, Section 3 explains how the effect of auralization on the measured scale of sound quality is addressed by a comparative evaluation experiment.

2. First experiment: Free-sorting task

Sixteen different systems were recorded by AKG C451B cardioid microphones in a semi-anechoic room, often at 3 different functioning speeds, and at 2 different positions (respectively at the inlet and outlet vent). A total of 92 different sounds was included in the recording database. These recordings are too numerous to be used in the experimental paradigm presented in Section 3. A sound dataset for this kind of experiment should not exceed 20 elements. For that reason, a reduced sound dataset is needed. A free-sorting task experiment was then conducted for that purpose.

2.1. Stimuli

The 92 recordings are already too numerous for a free-sorting task, which allows yet for the use of a relatively high number of stimuli. As a reasonable trade-off, this dataset was reduced to half its original size. We decided to select 3 representative samples for each of the 16 systems, that include at least one sound per recording position and 2 different speeds for each system. Finally, the sorting should not be based upon loudness variations. Therefore, the resulting 48-sound dataset was equalized in loudness according to Zwicker and Fastl's model [2] using an iterative algorithm conceived to restrict loudness difference to 1% or less of a reference value. The final sound dataset was then constituted of 48 loudness-equalized, 1.5 sec. long, monophonic sounds.

2.2. Apparatus

The task was performed through a Matlab Graphical User Interface (GUI) handling sound playback and recording of the listeners' response data. The sounds were played through an RME Fireface 400 audio interface and Sennheiser HD650 headphones.

2.3. Participants

Twenty-one participants (15 men, 6 women, aged between 20 and 29) volunteered as listeners for this experiment, all of which reporting normal hearing.

2.4. Procedure

At the beginning of the experiment, participants were given written instructions presenting the context of the study and explaining the task to accomplish. They had to group the 48 sounds into as many categories as they wished according to the sounds' similarity. Similarity criteria were left to the choice of the listeners. In the GUI, dots were associated to the sounds that could be played (double-click) and moved (drag and drop) on the screen so as to graphically form the categories.

2.5. Results

For each participant, the experimental data consist of a matrix coding the set partitions, that is to say, where each cell (i, j) is '1' if the participant has grouped sounds i and j into the same category, and '0' otherwise. These individual matrices are then averaged over the panel of participants to form a cooccurrence matrix, with values between 0 and 1. The complement to this matrix can be interpreted as a distance matrix [3].

We derived a hierarchical tree representation from these data using an unweighted arithmetic average clustering (UPGMA) analysis algorithm (see [4]). In such a representation, the height of the node that links two sounds ("leaves" of the tree) is the cophenetic distance that models the distance between two sounds as derived from the experimental data. The cophenetic correlation coefficient which corresponds to the Pearson product-moment correlation between the cophenetic distances and the experimental distances is 0.82. The tree representation is shown in Figure 1.

Among the 103,776 triplets that can be formed out of 48 sounds (all possible permutations considered), 77% follow the ultrametric inequality. This value is not as high as could be expected in this kind of experiment, but it should be remembered that the reason for conducting this experiment is to reduce the size of the studied dataset by sampling across the main categories rather than to obtain a realistic perceptual structure of representation of the sounds. Indeed, given the similar nature of the considered sounds, a continuous multidimensional representation, such as the timbre space, would fit better the way they are perceived (see [5], where the "motor" category identified by the authors would fit the kind of sounds studied here). But the type of experiment aiming at obtaining such a representation also requires a reduced sound dataset, which would have led anyway to the same kind of analysis as the one performed here.

2.6. Discussion

From this experiment we obtained a hierarchical representation of the original 48-sound dataset. We now need to derive the main sound categories that constitute the dataset from this representation and to select representative samples of each category in order to form the reduced dataset that will be used in the subsequent analyses.

The main categories were identified by "cutting" the tree at the particular threshold value of the cophenetic distance of 0.7. Nine categories were then extracted and are identified on Figure 1 by different colors and separated by dotted lines. In order to select at least one example of each system and to keep the representativeness of the size of each category in the final item selection, we chose to select 3 items in the large categories (the two leftmost on Figure 1), 2 in the

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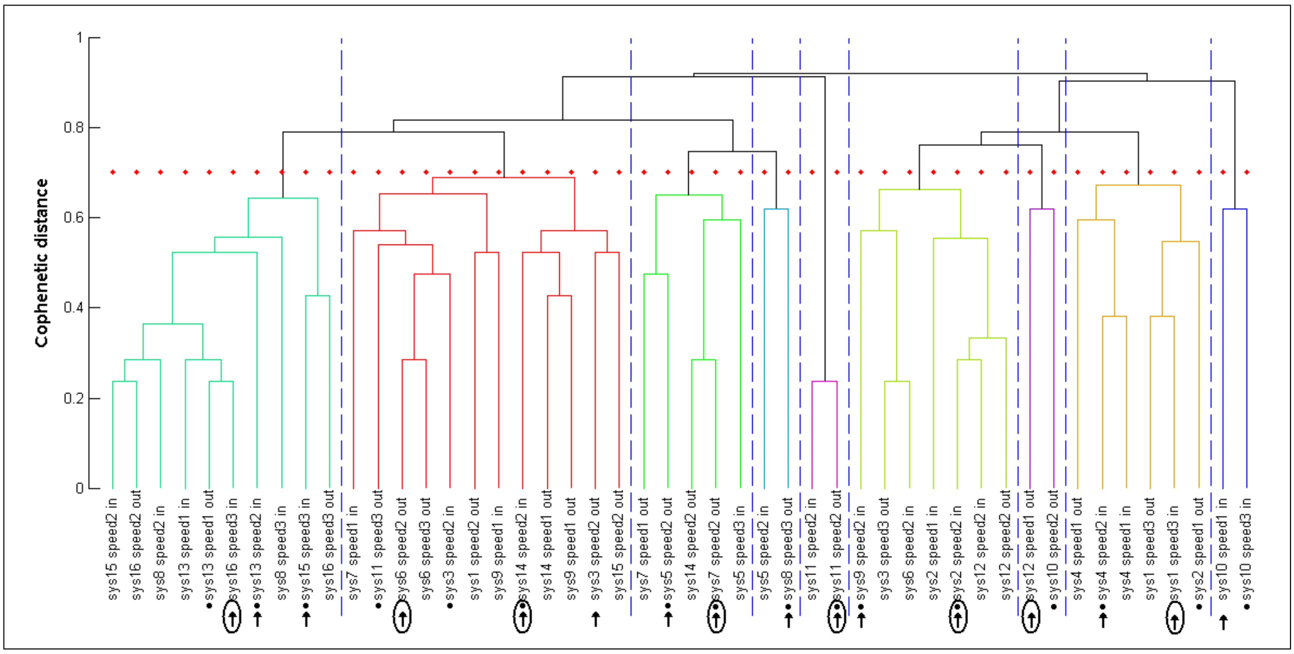

Figure 1. Tree representation of the results of the free-sorting experiment. "sys", "in" and "out" stand respectively for "system", "inlet vent" and "outlet vent". The dots and arrows under the recording names indicate respectively the first and final selections. The circled arrows correspond the 8-item dataset further used in the comparative evaluation experiment with auralized listening conditions.

middle-sized ones (2nd, 4th and 7th from the right), and 1 in the remaining 2-sound categories. This represents a total of 16 sounds, one per system. The selection was performed according to Rosch's prototype definition [6]: a prototype is the item of a group that is at the same time the closest to the other ones of the group and the farthest from those of the other groups. A criterion was built to apply this definition to the representative samples' selection according to the experimental distances. The obtained samples are indicated by the dots under the recording names on Figure 1. However some adjustments were brought to this automatic selection in order to obtain one recording per system, and to keep the representativeness of the different speeds and positions of recording, as well as a relative validity regarding Rosch's prototype definition. This final selection, that constitutes the sound dataset that will be used in subsequent experiments, is indicated by the arrows under the recording names on Figure 1.

3. Second Experiment: Comparative evaluation task in auralized conditions

This experiment represents the main point of interest of this study. The aim is to compare the perceived sound quality of the recorded sounds of ATS when presented in either anechoic or auralized conditions. This experiment has not been conducted in the former case yet. This section thus present the preliminary results obtained in the latter case.

3.1. Stimuli

Even though the sound dataset constituted through the first experiment (section 2) is made out of 16 sounds, one should keep in mind that we are comparing the effect of the auralization for two different simulated rooms. Therefore, this dataset needs to be reduced further to 8 items. The whole initial 16-sound dataset will be used in the experiment with anechoic conditions (yet to be conducted). The dataset reduction to 8 items – indicated by circled arrows on Figure 1 – was performed regarding the representativeness of the sound categories and of the different types of systems under consideration.

To simulate a realistic sound environment for the ATS sounds, the anechoic recordings were auralized using the *Auralias* program [7] for two configurations. Auralization is the audible rendering of a measured or simulated acoustic environment [8]. The anechoic recordings were thus convolved with computed room impulse responses (RIR).

The Auralias system combines the image source method for the direct sound field and the first specular reflections with the ray-tracing software *Salrev* [9] for the diffuse reflections and the late part of the RIR. Finally the sound reproduction is performed in an immersion studio equipped with 6 loudspeakers disposed on a circle around the listener's position (2D vector base amplitude panning system [10]).

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Two room configurations were simulated: a 4-by-4-m^2, 3-m-high individual office and a 20-by-20-m^2, 3-m-high open plan office. Both rooms have one wall with a 2-m-high bay window on the whole length and are equipped each with a 0.9-m-high table – 2 by 1 m^2 for the individual office, 13 by 13 m^2 for the open plan office. The used materials are:

- painted plasterboard for the walls
- double-glazing for the bay window
- fibrous absorbent material for the ceiling
- fitted carpet over concrete for the floor
- wood for the tables

Finally, the sounds were experimentally equalized in loudness with 5 listeners. The final 16-sound dataset consisted of the 8 loudness-equalized, 4 sec. long recordings indicated by circled arrows on Figure 1, auralized by these two simulations.

3.2. Apparatus

The task was performed through a Labview 2010 Graphical User Interface (GUI) handling sound playback and recording of the listeners' response data. The sounds were played through an RME Fireface 400 audio interface and FAR XM6D loudspeakers in the immersion studio.

3.3. Participants

Nineteen participants (15 men, 4 women, aged between 19 and 25) volunteered as listeners for this experiment, all of which reported having normal hearing.

3.4. Procedure

At the beginning of the experiment, participants were given written instructions presenting the context of the study and explaining the task to accomplish. A comparative evaluation paradigm [11], which is a hybrid procedure between direct evaluation and paired-comparison, was used. Figure 2 shows the Graphical User Interface used for this paradigm. The participant was asked to evaluate each sound on a scale between 0 for the most unpleasant sound to 10 for the most pleasant. He/she was given the possibility to play any of the sounds of the dataset and to evaluate it or to modify his/her evaluation at any time. Once every sound had been listened to and evaluated at least once and when the participant was content with his/her evaluations, he/she would validate the evaluations which would end the experiment session.

3.5. Results

Figure 3 shows the results of the experiment as the evaluations averaged over the panel of listeners for each sound.

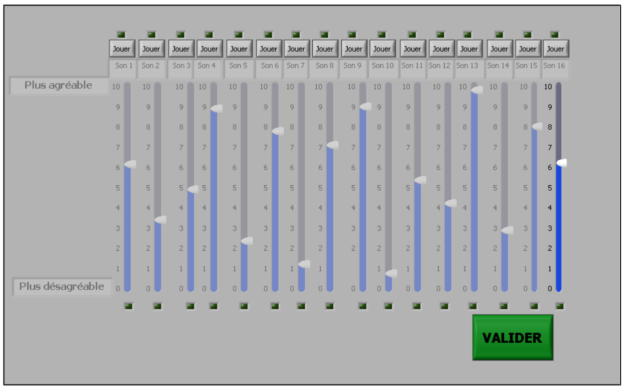

Figure 2. Labview 2010 Graphical User Interface for the comparative evaluation (0 corresponds to "most unpleasant", 10 corresponds to "most pleasant").

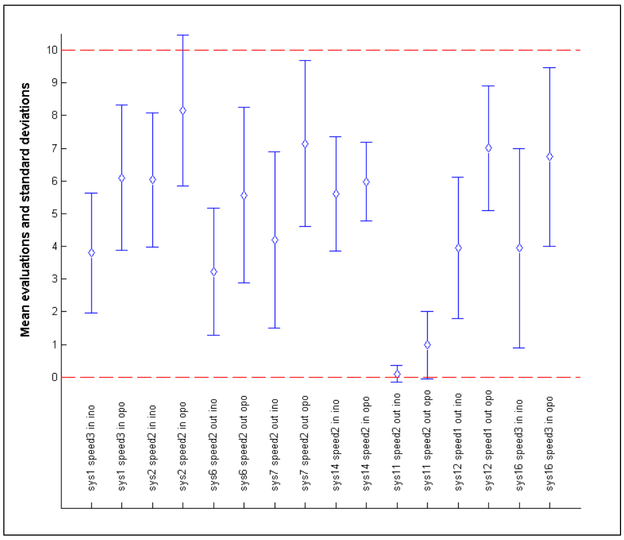

Figure 3. Mean evaluations and standard deviations (0 corresponds to "most unpleasant", 10 corresponds to "most pleasant"). "ino" and "opo" stand respectively for "individual office" and "open plan office".

3.6. Discussion

The results of the experiment are still under analysis. Nevertheless, a few observations can be made from these preliminary results. It seems that the second auralization (open plan office) tends to increase the evaluation of the measured sound quality to a reasonable extent. Even though, this tendency seems to have a smaller importance as compared to the timbre differentiation of the sounds (the extent of the evaluation differences between the recordings under the same auralized condition). This observation needs to be confirmed in a more formal way, probably using statistical hypothesis testing.

4. Conclusion

Common experimental procedures were used in this study to address the influence of room acoustics' fac-

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tors on the sound quality evaluation of ATS. An auralized sound dataset was constituted thanks to a free-sorting experiment over a large recording database and an auralized tool managing virtual Room Impulse Response calculation and 2D vector base amplitude panning reproduction performing playback on 6 loudspeakers in an immersion studio. The sound quality of this dataset's items was then evaluated through a comparative evaluation experiment. The results of this last experiment are still under study. Auralization and room acoustics' factors tend to have a significant influence especially on an absolute scale. How much these factors affect the measured sound quality still needs rigorous quantification.

To our opinion, the ecological relevance of the conditions for perceptual measurement in common experimental procedures are to be questioned. The sound as emitted by the source is indeed modified by room acoustics' characteristics before reaching the listener.

Furthermore, we observed some listeners bewildered by the task to be performed. It should be recognized that the acoustic impact of such systems in our environment does not typically occurs through careful listening of the sound. Rather, the sound intrudes into current activities during everyday life. Thus it might be relevant to focus on the effect of such sounds while attending to a concurrent task or carefully listening to another sound, thus shifting the listener's attention away from the ATS sound. We are planning to address this issue further in the course of studying ecological factors' influence on sound quality evaluation.

Acknowledgement

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