Chapter 4

Discussion

4.1 General research solution

The Introduction described that the main objective of this doctoral work was:

> **To provide methodological contributions for the improvement and homogenization of the listening tests currently employed to evaluate and enhance the representativeness of the indicators in the three areas of study.**

The work and the different experiments conducted during the course of this thesis, based on difference testing, have allowed the identification and proposal of improvements that could set the foundations of a common methodological framework for listening tests in the areas of sound insulation, room acoustics and soundscapes. These methodological contributions, in which bias has been carefully addressed, have overcome most of the shortcomings of the commonly used methodologies and may allow for a more accurate assessment of the representativeness of the acoustic descriptors employed today. Additionally, the advantages of an analysis by means of Thurstonian models have also been evidenced. The use of these for the analysis of the results enables a fair comparison of the different research conducted within the same scope by different researchers and encourages collaborative work to be done which, by means of meta-analysis, may lead to a faster and more relevant improvements of the current acoustic descriptors.

4.2 Results

This section presents the main results obtained from the research undertaken in each of the three areas of study.

4.2.1 Sound Insulation

Paper B presents the results of **Listening test #1**, carried out on the basis of the methodological contributions proposed in **Paper A**. This listening test, which was conducted by a large sample of 119 participants, was aimed at assessing the annoyance perceived by the participants for different façade sound insulation conditions under several types of urban sounds. The results showed that, on average, the current SNQs obtained correlations between 30.1% and 70.9% with the perceived annoyance. In particular, the R_w was found to be the most representative of the current SNQs for the studied situations, while quantities including the C_{tr} spectral adaptation term were found to have the worst performance.

A detailed inspection of the judgments for some of the compared stimulus pairs revealed that the spectral relevance of the currently employed reference spectra for the calculation of SNQs is not adequately matched with the perception of annoyance. In this way, spectral differences in frequency bands of little relevance according to the current reference curves resulted in significant perceptual changes in the participants, and vice versa.

An optimized reference spectrum ($L_{opt-urban}$) was also proposed for the calculation of a spectral adaptation term for façades ($C_{opt-urban}$) based on the test results. The correlation between the $R_w + C_{opt-urban}$ and the perception of annoyance was on average 77.2%, significantly increasing the representativeness of existing SNQs.

4.2.2 Room Acoustics

Paper C reports the results of **Listening test #2** carried out to evaluate the influence that the test protocol has on the ability to discriminate subtle differences between stimuli in room acoustics. For this purpose, **Listening test #2**, in which seven overall difference testing protocols were assessed, was undertaken by an extensive sample of 134 participants. The results of this test were compared through the Thurstonian measure of sensory difference *d'*.

The analysis highlighted that the operational power of the seven protocols was significantly different. That is, discrimination changed significantly depending on the protocol chosen to assess the degree of perceptual difference. In particular, it was observed that the ABX and Triangle protocols provided the lowest discrimination capabilities and, therefore, had the worst operational power. In contrast, the CR-DTF and CR-DTFM protocols allowed the highest discrimination. The remaining protocols (SD, CR-SD and A/NotA-R) enabled a fair discrimination.

It was also found that the different protocols studied were affected to different extents by experimental effects such as those of sequence, fatigue and learning, with the CR-DTF protocol being the most robust with respect to these effects.

4.2.3 Soundscapes

Paper D studied the usefulness of different statistics of the four main psychoacoustic indicators (i.e., *N*, *S*, *R* and *FS*) to describe the auditory perception of a sample of participants to urban environments with different geometrical features. To this end, a quantitative study was carried out employing automatic clustering algorithms, whose results were perceptually validated by means of **Listening test #3**.

The automatic clustering analysis determined that the percentiles *N5*, *N50*, *N95*, *S5*, *S50*, *S95*, *R10*, *R50*, *R95*, *FS10*, *FS50* and *FS95*, as proposed in [52], indeed allow to acoustically classify urban environments with similar architectural features of road and pedestrian width and building height, considering traffic the main source of noise. This clustering analysis was more robust for partitioning clustering algorithms, such as K-means, than for hierarchical algorithms. The automatic clustering also allowed to observe a high stability of soundscapes on different days and times of the year for the same period of the day, as the different recordings of the same soundscape tended to be clustered together strongly.

During **Listening test #3**, as detailed in **Paper D**, two listening test tasks were conducted by a small sample of 17 participants. The results of this listening test allowed to validate the objective outcomes of the clustering. On the one hand, the results of the first task reported that pairs of soundscapes belonging to the same cluster according to the partitioning clustering were reported as very similar during the listening test, while pairs of soundscapes belonging to different clusters showed low degrees of perceptual similarity during the listening test. Nevertheless, some results of this task were inconsistent with the automatic clustering, as it is highlighted in **Paper D**.

Moreover, for the second task, regarding human classification of soundscapes, participants were consistent with the automatic clustering, for most clusters, with correspondences of between 43.8% and 77.1%. However, for some clusters, the success rate was very low. This low success rate for some clusters could be derived from the particular clustering algorithm employed or from the inability of the employed percentiles of the psychoacoustic indicators to faithfully represent the acoustic features of those particular soundscapes. This suggests that further research needs to be carried out to investigate other types of clustering and percentiles of the psychoacoustic indicators, that could be of help in explaining particular situations.

4.2.4 Additional relevant results

Additional research was conducted in the areas of sound insulation and room acoustics. Most relevant results of this additional research were presented at international conferences and are briefly summarized below.

Regarding sound insulation, **Paper F** related with **Listening test #1**, presented at a conference prior to the publication of **Papers A and B**, showed that the position of a window rolling shutter has a significant influence on the annoyance perceived by inhabitants. In particular, it was found that extending the rolling shutter generally increases the objective sound insulation and reduces the perceived annoyance indoors, although in some cases the results may vary for particular urban noise sources. However, the calculation of Thurstonian models at the time of publication of this conference paper was not yet achieved and therefore the results can be subject to further analysis through Thurstonian analysis in the future.

Additionally, **Paper I** presented a review of the methodological features of the most relevant listening tests conducted in the area of sound insulation. This paper highlighted that very differing testing methodologies have been employed over the years, which hampers the comparison of results. This article also highlighted the advantages of using collaborative research to solve some of the unknowns that currently exist in the area of sound insulation.

Regarding room acoustics, **Paper E**, which was presented at a conference prior to the publication of **Paper C**, reviewed the main testing protocols employed over the years to address the determination of JNDs for several room acoustical parameters. Its main result highlighted the high heterogeneity of protocols currently employed by the different researches addressing similar aims.

In addition, **Paper G**, which this author coauthored, also carried out prior to **Paper C**, assessed whether a sample of participants was able to perceive a significant difference between recordings carried out in situ and auralizations of those same situations using three-dimensional acoustic models obtained with Odeon. In particular, a musical and a speech signals were tested in two rooms, one being highly reverberant and the other one rather dry. The results of this listening test, in which an A/NotA-R protocol was employed, were analyzed through the proportion of correct responses (P_c) as, at that time, Thurstonian models were not yet proposed by this author for the analysis of listening test results. These results showed that between 75% and 100% of the participants were able to perceive a difference between real and auralized stimuli. In particular, 75% of the participants perceived a significant difference in the dry room for the musical signal and 100% of them perceived a significant difference in the highly reverberant room for the speech signal, the rest of the situations being in this range. An analysis by means of Thurstonian models is to be expected.

Lastly, **Paper H**, in which this author participated, highlighted that the correlation between the clarity descriptor C_{80} and the perceived clarity varies drastically for different sound samples and different rooms and was found to be between 13.0% and 97.1% for the different rooms and sound samples tested.

4.3 Conclusions

The main conclusions of this doctoral work are presented in accordance to the objectives described in the Introduction:

- **Analysis of the strengths and weaknesses of current listening test protocols.**

As this manuscript and the introductory sections of **Papers A and C** have shown, there is no general consensus on how listening tests should be conducted in the areas of sound insulation, room acoustics and soundscapes for their results to be accurate, unbiased and highly relevant.

Paper A highlighted how scaling methods, commonly used in the field of sound insulation, are susceptible to various sources of experimental and analysis bias and how these issues can be overcome by the use of difference testing. This paper also highlighted that the apparent advantage of scaling methods (i.e., having a quantitative measure of perceptual evaluations compared to difference testing) can be addressed by the use of Thurstonian models.

Regarding the area of room acoustics, **Papers C and E** have shown how listening tests in this area have been carried out and analyzed in a heterogeneous way using different testing protocols. It is further explained how this fact has led to inconsistent results in several investigations even when the same objective was assessed. In addition, **Paper C** has shown how some of the most commonly employed listening tests in this area (e.g., ABX and Same-Different) have low operational power and are subject to experimental effects and should not be generally used for perceptual evaluations of subtle differences.

Finally, in the area of soundscapes, it has been shown in this manuscript that listening tests are based on the same procedures as in situ surveys, generally based on Likert-scale questionnaires, and that the advantages of listening tests over in situ surveys, such as the possibility of assessing different soundscapes during the same test, are therefore being neglected.

In addition, **Papers A, C, E and I** highlighted how the use of heterogeneous protocols without proven validity in these areas hinders the comparison of results of different research studies and the implementation of meta-analyses that could lead to more relevant results. It is therefore considered essential not only to conduct research aimed at resolving acoustic questions in these areas, but also that the listening test methodologies employed in these researches are homogeneous across researches, accurate and powerful.

- **Identification of methodological improvements, based on a common ground, that could be used for the definition of more robust, accurate and informative methodologies for the design, performance and analysis of listening tests in each of the areas.**

The work of this doctoral thesis has led to the proposal of methodological contributions, based on difference testing, for the design, performance and analysis of listening tests in the areas of sound insulation, room acoustics and soundscapes.

Paper A gives a detailed account of the sources of bias that can affect the performance of listening tests in the area of sound insulation and outlines how to reduce their influence. It also proposes the 2-AC attribute-related difference testing protocol for conducting listening tests in this area. This protocol, of novel application in the area of sound insulation, allows to obtain very precise characterizations of the perceptual differences between different insulation elements through the use of Thurstonian models.

With respect to the area of room acoustics, a CR-DTF overall difference testing protocol has been proposed for the performance of listening tests aimed at detecting small auditory differences, such as those employed for the determination of JNDs and for the assessment of the perceptual difference between real measurements and auralizations in the area of room acoustics. This protocol (CR-DTF) reported the greatest operational power among all the protocols evaluated in **Listening test #2**, as described in **Paper C**, and was also the least influenced by experimental bias effects.

Finally, **Listening test #3**, presented in **Paper D**, evaluated the suitability of difference-based listening tests as a complement to perceptual assessment of soundscapes using questionnaires. Two tasks based on difference testing were proposed and proved to be useful for assessing perceptual similarity between different soundscapes. However, these tasks are a statement of intent and need further development to constitute robust listening tests protocols for the assessment of soundscapes.

Thurstonian models and their distance metric *d'* have been strongly promoted in this thesis as the recommended method for the analysis of difference-based listening tests in acoustics, and their strengths have been highlighted in **Papers A, B and C**.

- **Assessment of the representativeness of the current indices by conducting listening tests following the methodological contributions.**

The results of **Listening tests #1 and #3** have allowed to assess the adequacy of some of the descriptors and thresholds currently used in the areas of sound insulation and soundscapes.

In particular, in the area of sound insulation, the results of **Listening test #1**, presented in **Paper B**, have shown that the current SNQs, and in particular those employing the traffic spectral adaptation term (C_{tr}), do not provide a good representation of the perceived sound protection provided by different façade insulation elements under the excitation of different urban sounds and that, therefore, the determination of more representative SNQs is convenient.

Finally, **Listening test #3**, presented in **Paper D,** has allowed to perceptually verify that some statistics of the psychoacoustic indicators Loudness (*N5*, *N50* and *N95*), Sharpness (*S5*, *S50* and *S95*), Roughness (*R10*, *R50* and *R95*) and Fluctuation Strength (*FS10*, *FS50* and *FS95*) could be used to determine the perceptual similarity of different soundscapes with respect to their architectural features. This result could have implications for urban development, allowing urban planners to foresee through the use of psychoacoustic indicators how environments with similar characteristics to existing ones would be perceived.

Consequently, these listening tests have verified the need for research through precise, unbiased and highly informative methodologies using humans as a measuring instrument in order to obtain more representative descriptors of the perceptual complexity of the human auditory system.

- **Verification of the usefulness of the proposed contributions for the development**

of indicators that are more representative of subjective perception.

In this doctoral work, and in particular in **Paper B**, it has been exemplified how the results of listening tests following the described methodological contributions have allowed the use of the quantitative metric *d'* as perceptually representative input data in algorithms aiming at the improvement of current indicators.

In particular, the *d'* estimates have been used in an optimization algorithm that has led to a reference spectrum ($L_{opt-urban}$) perceptually validated for the calculation of a spectral adaptation term ($C_{opt-urban}$) yielding significantly higher correlations with subjective perception than any of the current SNQs.

It is expected that similar approaches can be followed that make use of the *d'* estimates resulting from listening tests in the other two areas as input data to explore or identify more representative indicators in them. Consequently, it's the aim of this author to deeper explore the applicability of this and similar approaches, based on optimization, automatic classification and automatic learning, to the other two areas of study, on the basis of the methodological contributions proposed for the development of listening tests in the areas of room acoustics and soundscapes.

4.4 Future lines of research

This doctoral thesis has revealed that there is still considerable work to be done on the improvement of perceptual descriptions in the areas of sound insulation, room acoustics and soundscapes. Consequently, this author intends to continue his research in these areas both by making further methodological contributions as well as by conducting listening tests aimed at improving existing indicators.

As described in **Paper I**, this author sees collaborative research as a tool that can enable faster progress of research in these areas. Consequently, it is intended to continue improving the collection of applications developed during this thesis to make it freely available to other researchers in the near future. Additionally, it is expected to create a web platform where other researchers relying on the methodological contributions proposed by this thesis to conduct their listening tests can contribute to a collaborative database. This would allow meta-analyses to be carried out, from which they could all benefit. The existence of a collaborative database could also facilitate the use of very powerful tools such as machine and deep learning, which require large collections of data, to improve current indicators.

Also, in the area of sound insulation, this author is currently conducting a research using the proposed methodological contributions to assess the influence that the low-frequency range, which is currently generating much scientific debate, has on the perception of annoyance. Additionally, it is hoped to carry out the same study as **Listening test #1** with other insulation elements and other types of incident noise in order to evaluate the perception of annoyance under other representative situations. Additionally, similar to what was done in **Paper C** for room acoustics, listening tests in the area of sound insulation are expected to be carried out through different testing protocols to verify that the conclusions drawn in other fields of sensory evaluation are fully applicable to the area of sound insulation. That is, to verify that the 2-AC protocol, proposed in **Paper A** on the basis of research results in other fields of sensory evaluation, is indeed the most operationally powerful attribute-related difference testing protocol also when applied to sound insulation.

Furthermore, in the area of room acoustics, it is intended to carry out several studies using the proposed CR-DTF protocol to quantify the JNDs of the main classical parameters, considering a variety of room acoustical behaviours and types of sound. It is also expected to use the results of these listening tests to train an automatic decision algorithm to determine whether a perceptual difference exists between two room impulse responses from the signals only, without the need of the classical parameters and their JNDs.

Concerning soundscapes, a collaboration with international researchers is currently underway to investigate in more detail which percentiles of psychoacoustic indicators have a greater relevance in the perception of different features of urban environments and their main noise sources. This research, which complements that included in this doctoral thesis, has already allowed to verify, by means of other analysis techniques such as Principal Component Analysis (PCA), that the conclusions drawn in **Paper D** are generally applicable to other cities and urban environments. Furthermore, it is also enabling the identification of the percentiles with a higher correlation with each of the architectural features provided in **Paper D**. Additionally, it is intended to further develop the tasks presented in **Listening test #3** to improve their robustness and to allow the application of Thurstonian models to the analysis of their results.

Finally, it is also expected to investigate whether the use of listening tests based on difference testing can additionally be helpful in finding subtle differences between auditory stimuli in other areas different from those studied during this thesis. In particular, it is expected to evaluate the applicability of listening tests based on difference testing for the determination of subtle differences between echo cancellation algorithms.

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