



# **CSTB - Projet Environnement et ambiances : effet des basses fréquences sur le confort acoustique - tests psychoacoustiques**

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## **Usages Santé Confort**

# **Environnement et Ambiances**

## **Effet des basses fréquences sur le confort acoustique – Tests psychoacoustiques**

### **Rapport final**

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**Février 2014**

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**Février 2014**

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## Résumé

Aux niveaux européen et international, des propositions d'harmonisation des indices de performance acoustique des bâtiments sont actuellement à l'étude (projets de normes ISO 16717-1 et -2). Dans ce contexte, des questions ont notamment été soulevées sur le choix de ces indices et sur la prise en compte dans leur calcul des basses fréquences (tiers d'octave 50, 63 et 80 Hz). Afin d'évaluer la pertinence de différents indices existants, des tests d'écoute sont menés sur un panel d'une vingtaine de personnes. Des extraits sonores sont préparés sur la base d'une modélisation de la transmission à travers différents types de façades et de cloisons du bruit généré par des sources extérieures ou intérieures au bâtiment. La gêne provoquée par ces extraits est évaluée et corrélée aux différents indices de performance. Les résultats semblent indiquer que les nouveaux indices proposés ne sont pas mieux adaptés pour représenter la gêne.

**Mots clés :** indices de performance acoustique ; basses fréquences ; confort ; évaluation subjective.

## Abstract

At the european and international levels, proposals to harmonize building acoustic performance indices are currently under study (ISO 16717-1 and -2 projects). In this context, questions have been raised concerning the choice of these indices as well as the integration of low frequencies theses indices calculation (third octave bands 50, 63 and 80 Hz). In order to assess the relevance of different existing indices, listening tests are carried on a panel of more than twenty participants. Sound samples are prepared by modelling the transmission of noise through different types of façade walls or separating walls or floors, for typical noise sources outside or inside the building. Annoyance is then rated and correlated to performance indices. Results tend to show that the new proposals of indices are not better suited to evaluate annoyance.

**Keywords:** acoustic performance indices ; low frequencies ; comfort ; subjective assessment.

## Résumé long

Aux niveaux européen et international, des propositions d'harmonisation des indices de performance acoustique des bâtiments sont actuellement à l'étude (projets de normes ISO 16717-1 et -2). Dans ce contexte, des questions ont notamment été soulevées sur le choix de ces indices et sur la prise en compte dans leur calcul des basses fréquences (tiers d'octave 50, 63 et 80 Hz). Les laboratoires et institutions impliquées dans la normalisation en acoustique du bâtiment au niveau français ont décidé de travailler ensemble afin d'évaluer la pertinence des indicateurs proposés par l'ISO et éventuellement d'en proposer de nouveaux. En effet, la définition de nouveaux indices acoustiques doit permettre d'évaluer de façon plus fidèle le confort pour les occupants des bâtiments.

Les travaux présentés dans ce rapport s'attachent à caractériser, par le biais de tests d'écoute, la relation entre différents indices de performance acoustique et le ressenti des occupants dans les bâtiments d'habitation. Des sources de bruit aérien présentes à l'extérieur et à l'intérieur du bâtiment sont sélectionnées de façon à représenter les principales sources de plaintes des habitants, mais aussi de manière à ce que leur contenu fréquentiel soit différent. Des extraits sonores sont préparés sur la base d'une modélisation de la transmission à travers différents types de façades et de cloisons ou planchers séparatifs représentatifs des systèmes couramment utilisés. Les participants aux tests doivent alors associer à chaque extrait une note sur une échelle de gêne. Les résultats de ces tests menés sur un panel d'une vingtaine de personnes sont présentés et commentés.

Les résultats obtenus tendent à montrer que la prise en compte des basses fréquences ne permet pas d'obtenir une meilleure corrélation entre les indices de performance acoustique et la gêne des occupants des bâtiments vis-à-vis des bruits aériens. Néanmoins, des tests complémentaires doivent encore être menés afin de valider la méthodologie. Une fois les sources de biais potentielles écartées, ce type de tests pourrait être étendu aux bruits d'impact.

## Table des matières

|                                                                                       |           |
|---------------------------------------------------------------------------------------|-----------|
| <b>INTRODUCTION.....</b>                                                              | <b>9</b>  |
| <b>1. CONTEXT .....</b>                                                               | <b>10</b> |
| <b>1.1 ISO 16717 proposals .....</b>                                                  | <b>10</b> |
| 1.1.1 Air-borne noise .....                                                           | 10        |
| 1.1.2 Impact sound .....                                                              | 10        |
| <b>1.2 Previous studies .....</b>                                                     | <b>11</b> |
| <b>1.3 Link to the on-going ACOUBOIS project.....</b>                                 | <b>13</b> |
| <b>2. DESCRIPTION OF THE TEST METHOD .....</b>                                        | <b>15</b> |
| <b>2.1 General principle.....</b>                                                     | <b>15</b> |
| <b>2.2 Test design .....</b>                                                          | <b>15</b> |
| <b>2.3 Experimental setup .....</b>                                                   | <b>15</b> |
| 2.3.1 Procedure .....                                                                 | 15        |
| 2.3.2 Stimuli presentation and rating .....                                           | 16        |
| <b>2.4 Production of the audio stimuli .....</b>                                      | <b>16</b> |
| 2.4.1 Filtering .....                                                                 | 16        |
| 2.4.2 Sound reproduction .....                                                        | 17        |
| <b>2.5 Participants .....</b>                                                         | <b>17</b> |
| <b>2.6 Results post-processing.....</b>                                               | <b>18</b> |
| <b>3. DESCRIPTORS UNDER STUDY .....</b>                                               | <b>19</b> |
| <b>3.1 Descriptors used by the French acoustic regulation.....</b>                    | <b>19</b> |
| <b>3.2 New proposals .....</b>                                                        | <b>19</b> |
| <b>3.3 Other descriptors .....</b>                                                    | <b>19</b> |
| <b>4. LISTENING TESTS ON INDOOR AIRBORNE NOISE.....</b>                               | <b>21</b> |
| <b>4.1 Selected sound sources and level setting.....</b>                              | <b>21</b> |
| <b>4.2 Selected separating walls and floors.....</b>                                  | <b>22</b> |
| <b>4.3 Results.....</b>                                                               | <b>24</b> |
| <b>5. LISTENING TESTS ON OUTDOOR AIRBORNE NOISE.....</b>                              | <b>27</b> |
| <b>5.1 Selected sound sources and level setting.....</b>                              | <b>27</b> |
| <b>5.2 Selected façade walls.....</b>                                                 | <b>28</b> |
| <b>5.3 Results.....</b>                                                               | <b>30</b> |
| <b>5.4 Additional tests.....</b>                                                      | <b>33</b> |
| <b>CONCLUSION.....</b>                                                                | <b>35</b> |
| <b>REFERENCES.....</b>                                                                | <b>36</b> |
| <b>ANNEXES .....</b>                                                                  | <b>38</b> |
| <b>ANNEXE 1 : PICTURES OF THE TEST ROOM.....</b>                                      | <b>39</b> |
| <b>ANNEXE 2 : QUESTIONNAIRE AND INSTRUCTIONS GIVEN TO THE TEST PARTICIPANTS .....</b> | <b>40</b> |
| <b>ANNEXE 3 : GRAPHICAL USER INTERFACE DEVELOPED FOR THE LISTENING TESTS .....</b>    | <b>41</b> |
| <b>ANNEXE 4 : EMISSION SPECTRA OF THE SOUND SOURCES USED IN THE TEST.....</b>         | <b>42</b> |



## Liste des tableaux

|                                                                                                                                |    |
|--------------------------------------------------------------------------------------------------------------------------------|----|
| Table 1: Overall responses to the questionnaire .....                                                                          | 18 |
| Table 2: Selected sources of interior noise .....                                                                              | 21 |
| Table 3: Selected separating elements .....                                                                                    | 22 |
| Table 4: Single Number Ratings of the selected separating elements .....                                                       | 23 |
| Table 5: Correlation coefficients (R) between performance descriptors and annoyance – Interior noise .....                     | 26 |
| Table 6: Selected sources of exterior noise .....                                                                              | 27 |
| Table 7: Selected façade walls .....                                                                                           | 29 |
| Table 8: Single Number Ratings of the selected façade walls.....                                                               | 30 |
| Table 9: Correlation coefficients (R) between performance descriptors and annoyance – Exterior noise.....                      | 32 |
| Table 10: Correlation coefficients (R) between performance descriptors and annoyance – Exterior noise (additional tests) ..... | 34 |

## Liste des figures

|                                                                                                                                     |    |
|-------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1: Calibration result for one of the sound stimuli.....                                                                      | 17 |
| Figure 2: Age and gender distribution of the test panel .....                                                                       | 18 |
| Figure 3: Frequency weightings used to calculate single number descriptors .....                                                    | 20 |
| Figure 4: Emission spectra of the selected interior noise sources .....                                                             | 22 |
| Figure 5: Acoustic performance of the selected separating walls and floors .....                                                    | 23 |
| Figure 6: Separating elements classified by average annoyance .....                                                                 | 24 |
| Figure 7: Relationship between performance descriptors and average annoyance – Interior noise (all sources) .....                   | 25 |
| Figure 8: Emission spectra of the selected exterior noise sources .....                                                             | 28 |
| Figure 9: Description of the lightweight façade element.....                                                                        | 28 |
| Figure 10: Acoustic performance of the selected façade walls.....                                                                   | 29 |
| Figure 11: Façade walls classified by average annoyance.....                                                                        | 31 |
| Figure 12: Relationship between performance descriptors and average annoyance – Exterior noise (all sources) .....                  | 32 |
| Figure 13: Relationship between performance descriptors and average annoyance – Exterior noise (all sources; additional tests)..... | 33 |

## INTRODUCTION

In the context of new ISO standard drafts for evaluating acoustic performance indices (ISO 16717-1 and -2 projects), questions have been raised concerning the choice of these indices as well as the integration of the low frequencies in these indices calculation. In order to assess the compliance of the ISO 16717 drafts to the European needs, the European technical committee CEN/TC 126 has launched applicability studies in October 2012 concerning airborne sound insulation related to external noise, airborne sound insulation related to internal noise and impact sound insulation. French acoustic laboratories and institutions involved in building acoustics standardization have decided to work together in order to investigate the relevance of the ISO proposed indicators and eventually suggest new ones. The goal in defining new acoustic indices is indeed to more closely evaluate building occupants comfort.

The work conducted concerns mostly extended listening tests. Noise sources from outside and inside a building are chosen so they correspond to those for which inhabitants mostly complain, but also so that their frequency spectrum is different. Representative façades including windows, separating walls and floors with their usual complements (linings, floor coverings, etc...) are selected. Listening sequences are then prepared for different levels of the different noise sources and the different building components (only direct transmission is considered). Listening tests are performed on about 25 persons of different ages and backgrounds.

Preliminary results of this work were presented at the Inter-Noise congress held in Innsbruck, Austria, in September 2013 [1]. Extended results and more details about the methodology are given in this report.

## 1. CONTEXT

### 1.1 ISO 16717 PROPOSALS

The ISO/CD 16717 drafts are briefly discussed in this section with the different advantages and disadvantages that have already been pointed out. It should be stressed that converting a measured frequency dependent data to a single number rating corroborating acoustic comfort or annoyance due to different types of noise either outdoor or in a neighboring apartment is quite a challenge. No perfect rating system valid for all building situation and noise types can be expected. The single number rating proposed in ISO/CD 16717-1 and ISO/NP 16717-2 drafts is based as previous ratings on a spectral approach with different reference adaptation spectra, but integrating frequencies below 100 Hz. The background for the proposed changes in ISO 717 standards is presented in [2].

#### 1.1.1 AIR-BORNE NOISE

Two different noise types are distinguished: outdoor traffic noise and noise from neighbor. In the draft standard ISO/CD 16717, two descriptors are proposed to deal with these noise types:  $R_{\text{traffic}}$  and  $R_{\text{living}}$ . Their definitions are given in section 3.2.

Remark: the two proposed indices, even if their name is new, are based on already existent index combinations ( $R_W+C$  or  $R_W+C_{tr}$ ) except that the frequency range starting at 50 Hz is made mandatory for laboratory results (instead of optional previously) and optional for in-situ measurements (depending on acoustic regulation in each country). The addition of the low frequency range (third octave 50 to 80 Hz) followed the conclusions of the study on subjective evaluation of noise from neighbors carried by Mortensen in 1999 [3].

At first, a third descriptor  $R_{\text{speech}}$  was proposed for speech noise (for privacy reasons). It has however been withdrawn from the draft standard.

#### 1.1.2 IMPACT SOUND

The proposed change for rating impact noise is much deeper, since a new impact sound reduction index is defined. A major reason for this proposed change is that this new index  $R_{\text{impact}}$  now increases (instead of decreasing for the presently used index  $L_{n,w}$  or  $L_{n,w}+C_I$ ) when acoustic performance with respect to impact increases [4]. However, the choice for the reference spectra to evaluate the new index  $R_{\text{impact}}$  allows obtaining a simple expression between the old and new indices

$$R_{\text{impact}} = 104 - (L_{n,w} + C_{I,50-2500}) \quad (1)$$

The adaptation term  $C_{I,50-2500}$  is included to take into account the annoyance at low frequencies following recommendations from [3].

It should be mentioned that one advantage of using sound reduction index is that it is presumably independent of the noise source. For example, to create listening stimuli in a reception room the noise source located in an emission

room can simply be filtered with the sound reduction index. However, for the proposed impact sound reduction index, this is not the case since it is still fully dependent on the impact source being the tapping machine. There is still no easy way to apply different impact sources (such as walking person or jumping children) with this proposed impact sound reduction index. Therefore, its interest appears to remain up to now quite limited.

## 1.2 PREVIOUS STUDIES

Listening tests have been already performed in order to evaluate the advantage or disadvantage of different ratings with respect to noise annoyance; the most recent and closely related to the proposed new ratings have been carried out at KUL in Belgium [5] and NRC in Canada [6].

In [5], two different walls (lightweight gypsum boards partition wall and masonry wall) having the same single value rating  $R_{\text{living}}$  but different sound insulation spectra  $R$  were considered with 64 different typical "living room noises". The stimuli with duration of 5 to 10 seconds were presented in pairs via headphones; the listening subjects were asked to indicate the louder stimuli for each pair. The results indicated that proposed "living noise rating" did not adequately correspond with perception due to an overestimation of the importance of low frequencies for sound at low intensities. Masking effects were not taken into account. The tests were carried out in an anechoic chamber, which obviously cannot represent a realistic situation such as being at home.

In [6], a number of 12 different spectrum weightings are considered for possible inclusion in the new ISO/CD 16717-1 standard. The 12 spectrum weightings were evaluated using previously acquired data consisting of annoyance ratings of speech and music sounds modified to represent transmission through 20 different walls with a wide range of sound transmission characteristics. Subjects rated the annoyance of each sound on a 7-point scale from 1 for "Not at all annoying" to 7 for "Extremely annoying"; the stimuli was produced by a loudspeaker system located 2 m in front of them and hidden behind a curtain. A background noise level of 35 dB(A) simulating a ventilation type noise was also produced in the listening room. The results showed that many of the spectrum weightings led to similarly accurate predictors of the annoyance due to transmitted music sounds and suggested that only a relatively small number of spectrum weightings could be justified. Based on these new analyses, 3 spectrum weightings were recommended for inclusion in the ISO/CD 16717-1 standard: living, traffic and a new improved speech spectrum weighting. It should be pointed out, the living spectrum weighting is equal to the already existing  $C_{50-5000}$  weighting, and is a very close approximation to the standard A-weighting.

From these two studies, it was believed that more listening tests could be performed to include different types of sound sources and to use commonly found French building elements (wall, floors, etc...). Furthermore, the listening tests were concerned with airborne noise; however, impact noise is also of interest since it is often a source of annoyance and the new proposed rating should also be evaluated.

Concerning impact noise, Bodlund [7] proposed an alternative reference curve for evaluation of impact sound insulation between dwellings based on a survey comprising measurements and interviews with tenants in eight housing areas. This work concluded that a straight curve with a positive slope of 1 dB per third octave band starting at 50 Hz and terminating at 1000 Hz was a very good alternative for a reference curve, while keeping the standard tapping machine as the sound source. A comparison of methods for rating the insulation of floors against impact sounds was performed in 1998 by BRE and CSTB [8]. Recording were obtained for four different floors, without and with two different floor coverings (plastic flooring and carpet), under two types of excitation: a modified tapping machine to simulate woman walking and a sand bag to simulate children jumping. The levels of statistical significance attained did not allow a firm recommendation. However, the results were consistent with those obtained by Bodlund [7] in terms of extending the frequency range down to 50 Hz and using a straight line of slope 3 dB per octave as a reference curve. The Dutch method was found to be the most satisfactory; the dB(A) method was also found better performing than the ISO method even though it was poor at relating physical and subjective rating of bare floors. In 1999, a study from Lundt university [9] demonstrated through listening tests using the standard tapping machine as exciter the loudness measured according to ISO 532B was better correlated to the subjective impression of the impact sound than the commonly used weighted value  $L_{n,w}$ ; high correlation coefficients were also obtained for the Bodlund index and  $L_{eq,A,F}$ . Further analysis [10] based on new data (in-situ measurements and tenants interviews) as well as some of Bodlund's data, combining hollow and solid concrete based and lightweight floors, resulted in a new proposal for reference curve. It was also demonstrated that if low frequencies have to be taken into account to a greater extent, high frequencies must also be considered so as to prevent the future adoption of heavy floor structures with hard floor coverings. An objective and subjective assessment of lightweight wood-framed floor assemblies was performed at NRC [11]. The stimuli were recorded in the laboratory and played back for the tests. They were presented by pairs and the test participants were asked to rate one sound with respect to the other one which was always the same for a given test, on a 1 to 9 scale (much less annoying to much more annoying). The results obtained with the Japanese impact ball were more highly correlated with subjective judgments. However, the results using the standard tapping machine and index that include the spectrum adaptation term  $C_{I,50-2500}$ , give the highest correlations for both types of impact sounds. This supports similar conclusions offered in [12], which included only objective analyses, but of a wider range of assemblies, and included walkers wearing shoes, as well as those presented in [3].

In 2011, a resident's survey (using questionnaire proposed by COST Action TU0901 [14]) and field measurements in apartment buildings was carried out in Sweden [13]; buildings were either with concrete floors and walls or with timber joist floors and walls. The results from these surveys were amended by data from previous studies to search for correlations between subjective ratings (by residents) and objective measurement results. A reasonable correlation was found between ratings and the calculated and/or the measured normalized impact sound pressure level  $L'_{n,w} + C_{I,50-2500}$ . However, for airborne sound insulation, the correlation between the ratings and the  $R'_w + C_{50-3150}$  was weak.

Through the COST Action TU0901 [14][1], descriptors for the acoustic performance of buildings have also been proposed:  $D_{nT,50} = D_{nT,w} + C_{50-5000}$  for airborne sound insulation,  $L_{nT,50} = L_{nT,w} + C_{50-5000}$  for impact sound insulation and  $D_{2m,nT,50} = D_{2m,nT,w} + C_{50-5000}$  or  $D_{2m,nT,w} + C_{50-31500}$  depending on type of outdoor noise for façade sound insulation. The proposed descriptors are standardized with respect to reverberation time; however the reference reverberation time of 0.5 s might not be representative at low frequencies.

Ratings method is necessary to reduce the complex spectra of insulation against airborne or impact sounds to a more convenient single figure index. The test of a good rating method is how well the resulting indices are correlated with subjective assessments of the insulation. From the short review of previous studies it can be seen that this is a difficult task. First of all, the building practice (type of walls and floors) are quite different in the European countries and even more throughout the ISO involved countries; thus it is questionable that "the perfect rating" can be found. Nevertheless, it appears that acoustic ratings could be improved; this however requires compromises and changes in building practice and regulation.

It should also be mentioned than a very large investigation, regarding on airborne sound insulation and impact sound insulation and the perception of external sounds in respect with the sound insulation performance between the source and the listener, has been undertaken in Finland. Preliminary results have been presented at the Internoise 2013 conference [15].

In parallel, a laboratory experiment was also conducted in Finland using listening tests to evaluate the correlation between single number quantities and disturbance perceived at home [16]. Sound stimuli were produced from recordings of representative sources of interior noise filtered with the sound reduction index of a selection of commonly used partition walls (measured down to 50 Hz). Six different noise sources and nine different walls were considered. Only direct transmission was accounted for. From the results of this work, the inclusion of low frequencies in the new single number quantity  $R_{\text{living}}$  was not recommended.

The French work program as presented in this report introduction will then just be a complement to these already conducted studies.

However, from the majority of the already conducted studies the proposed changes in rating methods in ISO/CD 16717 drafts by including the adaptation terms down to 50 Hz do not appear out of sense and not much different from what already exists, except for the impact sound insulation.

### **1.3 LINK TO THE ON-GOING ACOUBOIS PROJECT**

The French ACOUBOIS project with CSTB, FCBA and QUALITEL-CERQUAL as partners has been launched in 2010. The main goal of the project is to provide a prediction method for evaluating acoustic performance of lightweight buildings at the conception stage and as well as a database for acoustic performance of lightweight elements (wall, floor, façade and roof) fulfilling actual regulations (thermal, fire, humidity, etc....) for frequency range from 50 to 5000 Hz. In

order to test and validate the prediction method, in-situ acoustic measurements on about 30 different buildings should be performed, including airborne and impact sound insulation as well as service equipment noise. To further evaluate the discomfort sometimes reported in residential multi-family lightweight buildings, measurements of low frequency impact sound with a heavy soft rubber ball representative of jumping children are also included. Resident survey by face-to-face interviews based on questionnaire adapted from the one proposed by COST Action TU0901 [14] is also realized on ten different apartment buildings where acoustic measurements have been performed. This will hopefully help correlating acoustic indices from actual measurements and occupants perception. Acoustic measurements and resident surveys will also be implemented on some concrete based most common type French buildings in order to complete the picture. Most of these results should be available by the end of the year. It should be however stressed that since neither the building nor the residents were sampled in a statistical point of view, it will not be possible to interpret the results from these in-situ surveys as fully representative of multifamily buildings in France.

It is expected that from the results of these different underway studies, a common position for the French acoustic experts involved in the French Building Acoustics standardization committee can be reached; this common position could end up in proposals for amendment and modification of the proposed standard drafts.



## **2. DESCRIPTION OF THE TEST METHOD**

In this section, the listening test experiments are described and details about the methodology are given.

Lots of different types of listening tests can be found in the literature, each one having its advantages and drawbacks. The method used in this study is strongly inspired from the work by Hongisto et al. in Finland [16].

### **2.1 GENERAL PRINCIPLE**

The present listening tests aim at evaluating the correlation between various acoustic performance descriptors and the annoyance felt by building occupants when they are exposed to noise produced by their neighbors or by other sources outside the building.

For that purpose, audio stimuli are produced by filtering recorded sound samples with the transmission characteristic of different building elements, i.e. façades or separating walls and floors. The assumption is made that only direct transmission occurs. Different noise sources are considered for both interior and exterior noise. Noise sources are selected in a way that they are representative of sources encountered in daily life and that their frequency content is different.

Participants have to listen to the audio stimuli while imagining themselves to be at home, and rate them on an annoyance scale. Then a statistical analysis is performed to establish the relationship between the ratings given and the acoustic performance of the building elements considered.

### **2.2 TEST DESIGN**

### **2.3 EXPERIMENTAL SETUP**

The listening tests take place in a quiet room furnished like a living room with a reverberation time of about 0.5 s. The listening subject is comfortably sitting in front of a portable computer equipped with a mouse (see pictures in Annexe 1). The audio stimuli are played by two loudspeakers placed at the top of a shelf with an approximate distance of 1.5 m between them and hidden behind a thin fabric screen.

With only a fake window, the room has a relatively good sound insulation against exterior noise.

#### **2.3.1 PROCEDURE**

The listening tests follow a rather simple procedure: no hearing tests are performed on the participants, no rehearsal phase is proposed.

Participants are first given a sheet of paper (reproduced in Annexe 2) containing a short questionnaire and the instructions for the test. The questions concern the participant (age, gender, presence of identified hearing impairment) and his home (type of dwelling and environment) for eventual detailed analysis.



Once they are ready, participants take the test and can take as much time as they need to complete it. The test uses a MATLAB program running on a computer so that no intervention of another person is required.

### **2.3.2 STIMULI PRESENTATION AND RATING**

A direct scaling method has been chosen for this experiment, using a discrete scale from 0 (not at all annoying) to 10 (extremely annoying) as recommended in ISO 15666 [17].

The whole test is divided into 2 parts: first the stimuli corresponding to outside noise are played and rated, and then the stimuli corresponding to noise from the neighboring dwellings.

Within each of these parts, all the stimuli that correspond to a given sound source are presented together on the same screen (see Annexe 3). The listener can play each of these stimuli as many time as he wants by clicking a button and adjust the ratings using the corresponding cursors. Once he is satisfied with the ratings, the participant validates his choice and proceeds to the next sound source. At this level, previous ratings can not be longer modified.

Cursors have a red color and turn green once the corresponding stimulus has been played and rated. All stimuli have to be rated in order for the participant to validate his choice and go on to the next screen.

In order to compensate for any order effect on the test results, stimuli that are presented together are placed in a random order on the screen. Similarly, a random order is applied to the different groups of stimuli.

## **2.4 PRODUCTION OF THE AUDIO STIMULI**

The audio stimuli used in the test are obtained from recorded sound samples of the database of the Acoubat Sound software. The sound samples are representing noise produced in the emission room or outside the building and must be filtered to reproduce the transmission through façade walls or separating walls and floors.

### **2.4.1 FILTERING**

The initial audio sequences are filtered in third octave bands with the sound reduction index of building elements, taking only the direct transmission path into account. Digital filtering using second-order Butterworth filters is performed.

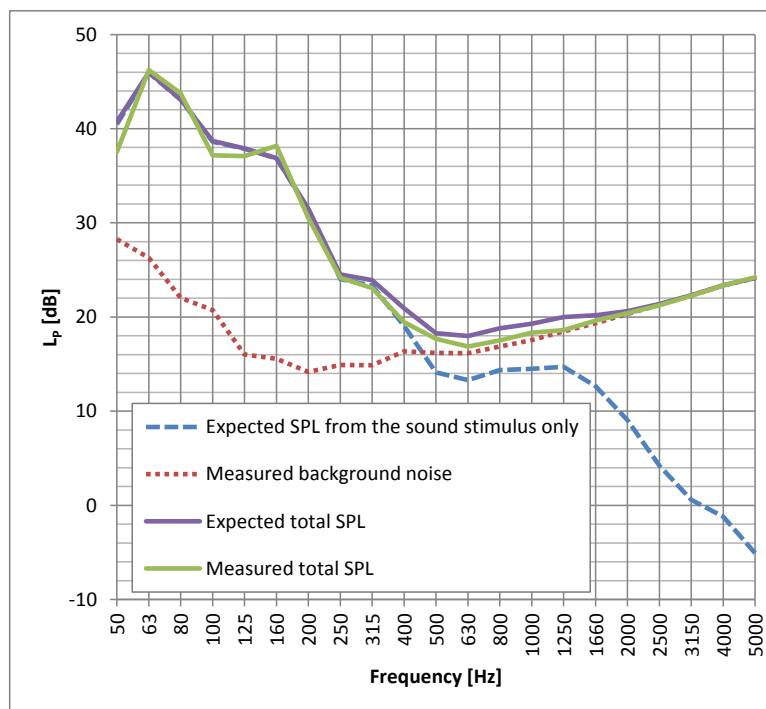
Remark : the sound samples are filtered in the range 50-5000 Hz, for which sound reduction index data are available. All the frequency content below and above this range is cut off. This may result in a lack of realism of the sound reproduction, in particular for noise sources that have a strong low frequency content (e.g. music, road traffic, airplane, construction works). Other techniques can be implemented in order to keep low frequencies in the signals, as in the work by Mortensen [3], Ordoñez et al. [18] or in the Swedish project Akulite

[13]. However, when evaluating the filtered sound samples before using them in the listening tests, this lack of realism was not detected.

## 2.4.2 SOUND REPRODUCTION

The sound stimuli are recorded as mono signals with a sampling frequency of 44100 Hz and encoded as 16-bit WAVE files. They are played by the computer running the MATLAB program (with its built-in sound card) connected to two Genelec 8020A active loudspeakers.

Once the volume knob on the loudspeakers is set, a calibration step is required to compensate for the frequency response of the whole electroacoustic system, which is most likely not flat in the frequency range of interest (especially in the low frequency range where the response of the loudspeakers drops). To that end, sound pressure level measurements are performed in the room with an averaging time of 15 s while some stimuli are played, and measured and expected spectra are compared. Then all the stimuli are filtered in third octave again, the filter characteristic being equal to the average difference between the expected and measured sound pressure levels. This procedure allows to reproduce the expected sound pressure level in the listening room within a 3 dB accuracy at all frequency bands (see Figure 1).



**Figure 1: Calibration result for one of the sound stimuli**

## 2.5 PARTICIPANTS

For a better reliability of the statistical analysis, it is important to perform the test with an important number of participants and that the panel is representative of the French population in terms of age and gender distribution, home environment, cultural background, etc.

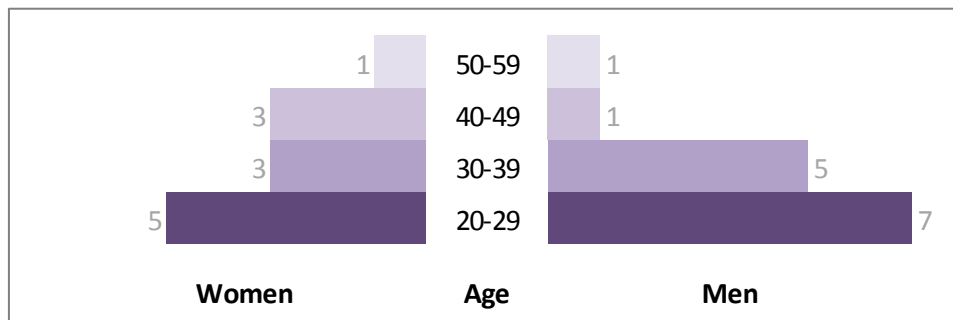
Due to the time available, 26 persons took the test. All test subjects got rewarded with a 10 euro gift certificate for their participation at the end of the test. Despite a large majority of them were working at CSTB, only a few were familiar with acoustics and had already participated in listening tests before. Results of the questionnaire are reproduced in Table 1. The age and gender distribution is represented in Figure 2.

Although a good balance between male and female subjects, it should be noted that the panel is mostly composed of rather young people, which is not really representative of the French population.

Remark: despite one participant was subject to light hearing problems, it was still decided to account for his responses since they were not significantly different from the responses of other participants.

**Table 1: Overall responses to the questionnaire**

| <i>Age</i>                         | <i>20-29</i> | <i>30-39</i>     | <i>40-49</i>            | <i>50-59</i> |
|------------------------------------|--------------|------------------|-------------------------|--------------|
| Number of participants             | 12           | 8                | 4                       | 2            |
| <i>Gender</i>                      | <i>Men</i>   | <i>Women</i>     |                         |              |
| Number of participants             | 14           | 12               |                         |              |
| <i>Identified hearing problems</i> | <i>Yes</i>   | <i>No</i>        |                         |              |
| Number of participants             | 1            | 25               |                         |              |
| <i>Home environment</i>            | <i>Urban</i> | <i>Rural</i>     |                         |              |
| Number of participants             | 17           | 9                |                         |              |
| <i>Home type</i>                   | <i>Flat</i>  | <i>Row house</i> | <i>Individual house</i> |              |
| Number of participants             | 18           | 1                | 7                       |              |



**Figure 2: Age and gender distribution of the test panel**

## 2.6 RESULTS POST-PROCESSING

All the participants have to rate the same set of sound stimuli. For each stimulus, all the ratings are averaged over the panel. Then a linear fit is performed between the average rating and the performance descriptor under consideration, following the method presented in [19].

A good performance descriptor is characterized by a decrease of the averaged annoyance with increasing performance, for all types of sound sources. Consequently, the Pearson correlation coefficient  $R$  is expected to be close to -1

for good descriptors. The correlation analysis is carried out by considering all the different situations (all building elements and all sound sources) and also at a more detailed level for each sound source independently. Distinction is made between interior and exterior noise.

### 3. DESCRIPTORS UNDER STUDY

In this work, 12 different Single Number Ratings (SNR) describing the protection against noise provided by building components are considered. They are all obtained from third octave band values of the sound reduction index  $R$ , either by comparison to a reference spectrum or by applying a given frequency weighting.

Some of them are already used in the current French acoustic regulation, and others are introduced by the new draft standard ISO/CD 16717-1.

#### 3.1 DESCRIPTORS USED BY THE FRENCH ACOUSTIC REGULATION

- **$R_W + C_{100-3150}$**  : as defined in ISO 717-1 [20], is obtained by comparison to the reference curve for airborne noise and addition of the adaptation term  $C$ , in the range 100-3150 Hz. It is used in the French acoustic regulation as the performance of building elements for sources of airborne noise located inside the building.
- **$R_W + C_{tr,100-3150}$**  : as defined in ISO 717-1 [20], is obtained by comparison to the reference curve for airborne noise and addition of the adaptation term  $C_{tr}$ , in the range 100-3150 Hz. It is used in the French acoustic regulation as the performance of building elements for sources of airborne noise located outside.

#### 3.2 NEW PROPOSALS

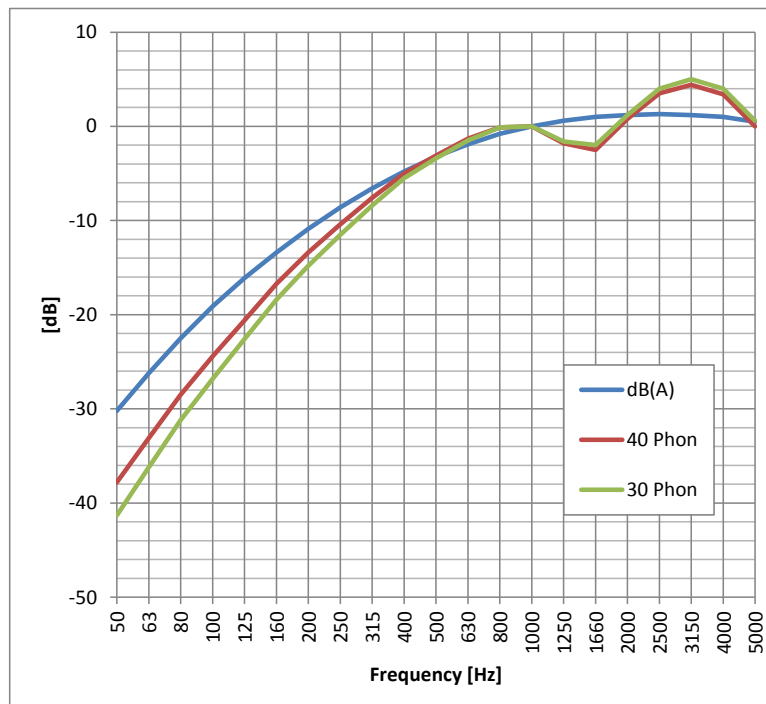
- **$R_{living}$**  : the "living noise sound reduction index" as defined in ISO/CD 16717-1, evaluated from 50 to 3150 Hz, representing insulation against "living noise" with an A-weighted pink noise spectrum as given for the previous spectrum adaption term  $C_{50-5000}$ .
- **$R_{traffic}$**  : the "traffic noise sound reduction index" as defined in ISO/CD 16717-1, evaluated from 50 to 3150 Hz, representing insulation against annoyance by traffic noise with an A-weighted traffic noise spectrum as given for the previous spectrum adaption term  $C_{tr,50-5000}$ .

#### 3.3 OTHER DESCRIPTORS

- **$R_{speech}$**  : the "speech sound reduction index", evaluated from 200 to 3150 Hz, representing speech privacy (formerly introduced by the new draft standard but recently removed after discussion).
- **$R_{living,85\%}$**  : similar to the "living noise sound reduction index"  $R_{living}$ , except that an alternative reference spectrum supposedly valid for 85% of real sound sources is used (formerly introduced by one of the standard draft version but then removed after discussion).

- **$R_W$**  : as defined in ISO 717-1 [20], is obtained by comparison to the reference curve for airborne noise without addition of any adaptation term.
- **$R_{100-5000} - dB(A)$**  : evaluated by applying the A-weighting spectrum in the range 100-5000 Hz.
- **$R_{100-5000} - ISO226-40Phon$**  : evaluated by applying a frequency weighting corresponding to the 40 Phon curve defined in ISO 226 [21] in the range 100-5000 Hz.
- **$R_{100-5000} - ISO226-30Phon$**  : evaluated by applying a frequency weighting corresponding to the 30 Phon curve defined in ISO 226 [21] in the range 100-5000 Hz.
- **$R_{50-5000} - ISO226-40Phon$**  : evaluated by applying a frequency weighting corresponding to the 40 Phon curve defined in ISO 226 [21] in the range 50-5000 Hz.
- **$R_{50-5000} - ISO226-30Phon$**  : evaluated Hz by applying a frequency weighting corresponding to the 30 Phon curve defined in ISO 226 [21] in the range 50-5000.

The A-weighting spectrum as well as the frequency weighting spectra corresponding to the 40 Phon and 30 Phon curves are represented in Figure 3. These two last weighting spectra are related to loudness threshold of audibility and are supposed to give a better representation of the sensitivity of human ear at normal sound levels encountered in a dwelling.



**Figure 3: Frequency weightings used to calculate single number descriptors**

## 4. LISTENING TESTS ON INDOOR AIRBORNE NOISE

### 4.1 SELECTED SOUND SOURCES AND LEVEL SETTING

The 6 sound sources listed in Table 2 were selected because they were representative of what building occupants complain most.

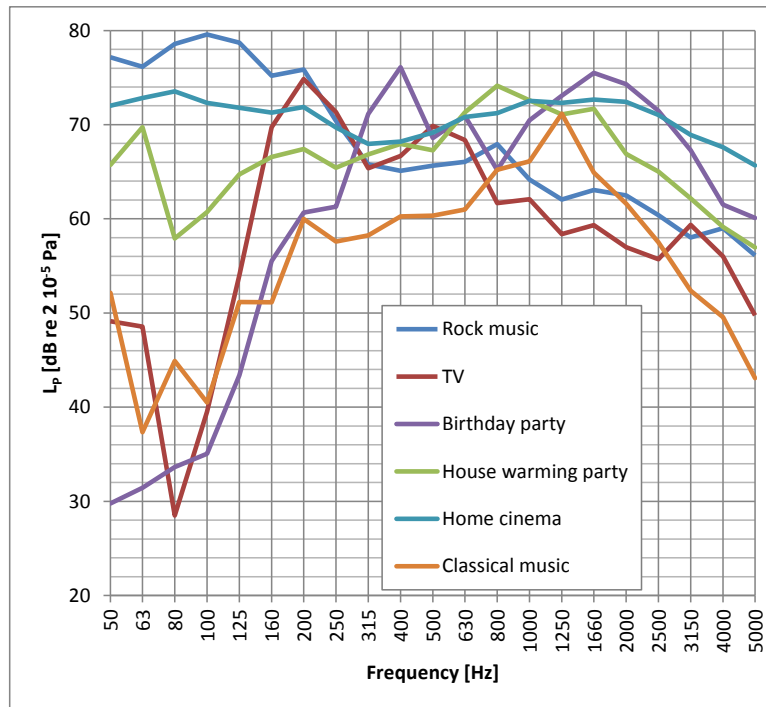
To keep the test duration within reasonable limits, only a certain part of the initial sound samples had sometimes to be selected. The spectra of the initial sound samples (before time selection and filtering) corresponding to each of the selected sound sources are given in Annexe 4. Other sources were available but were not selected, since their spectra were not significantly different.

**Table 2: Selected sources of interior noise**

| Source no. | Source type                                    | Duration [s] | $L_{eq}$ [dB] | $L_{Aeq}$ [dB(A)] |
|------------|------------------------------------------------|--------------|---------------|-------------------|
| 1          | Rock music                                     | 8            | 86            | 75                |
| 2          | Television (news program)                      | 20           | 79            | 74                |
| 3          | Birthday party (with singing voices)           | 14           | 83            | 82                |
| 4          | House warming party (with music and voices)    | 14           | 82            | 80                |
| 5          | Home cinema (war movie with blasts and voices) | 24           | 84            | 82                |
| 6          | Classical music                                | 14           | 75            | 75                |

Before being filtered with the sound reduction index of the separating walls and floors, different values of volume gain are applied to the sound samples so that the resulting levels are representative of a normal situation in the virtual "emission room" and that a good balance is found between them.

The emission levels of the 6 sound sources are represented in Figure 4.



**Figure 4: Emission spectra of the selected interior noise sources**

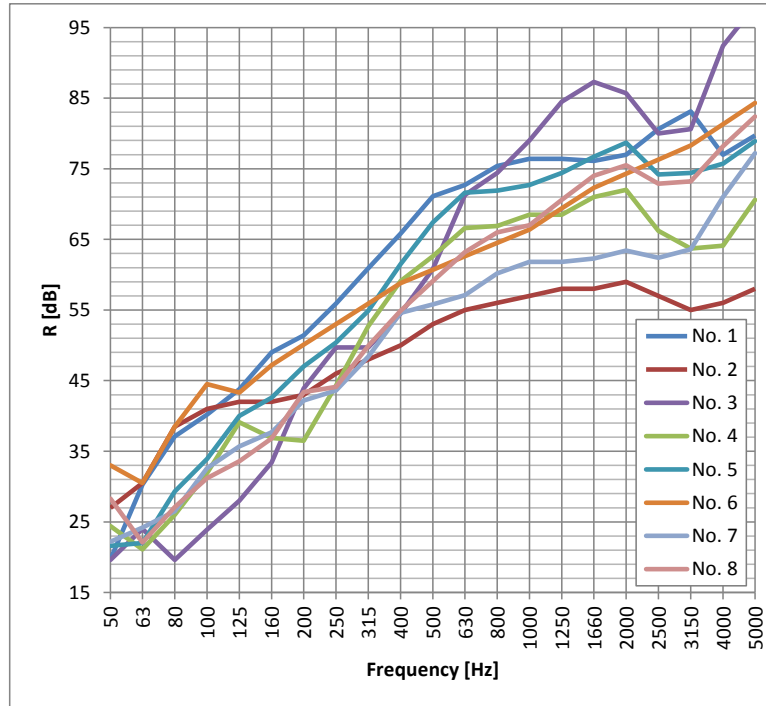
## 4.2 SELECTED SEPARATING WALLS AND FLOORS

In this part of the test, sound samples are filtered with the sound reduction index of the 8 following separating walls and floors.

**Table 3: Selected separating elements**

| Separating element No. | Description                                                                                        |
|------------------------|----------------------------------------------------------------------------------------------------|
| 1                      | Lightweight wall made of plasterboards mounted on double metallic frame                            |
| 2                      | Heavy wall made of 200 mm thick hollow concrete blocks                                             |
| 3                      | Lightweight plasterboard wall on double wood frame with internal bracing boards                    |
| 4                      | Lightweight plasterboard wall on double wood frame with external bracing boards                    |
| 5                      | Lightweight wall made of plasterboards on simple wood frame with an independent lining on one side |
| 6                      | Heavy floor made of 200 mm thick concrete                                                          |
| 7                      | Wooden floor with suspended ceiling and plastic floor covering                                     |
| 8                      | Wooden floor with suspended ceiling and parquet flooring                                           |

These building elements have very different acoustic performances, as shown in Figure 5. Table 4 summarizes the Single Number Ratings of these walls and floors.



**Figure 5: Acoustic performance of the selected separating walls and floors**

**Table 4: Single Number Ratings of the selected separating elements**

|                                       | Separating element No. |      |      |      |      |      |      |      |
|---------------------------------------|------------------------|------|------|------|------|------|------|------|
|                                       | 1                      | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
| $R_{\text{living}}$                   | 58.4                   | 54.0 | 48.0 | 51.8 | 54.7 | 61.0 | 52.5 | 52.5 |
| $R_{\text{traffic}}$                  | 43.8                   | 47.1 | 36.8 | 40.5 | 41.6 | 50.4 | 41.5 | 41.6 |
| $R_{\text{speech}}$                   | 71.8                   | 54.8 | 62.1 | 64.1 | 67.7 | 64.0 | 58.4 | 61.4 |
| $R_W + C_{100-3150}$                  | 64.0                   | 54.0 | 49.0 | 53.0 | 58.0 | 62.0 | 54.0 | 54.0 |
| $R_W + C_{tr,100-3150}$               | 57.0                   | 51.0 | 42.0 | 47.0 | 52.0 | 57.0 | 48.0 | 47.0 |
| $R_W$                                 | 66                     | 55   | 54   | 57   | 61   | 63   | 56   | 56   |
| $R_{100-5000} - \text{dB(A)}$         | 64.7                   | 54.4 | 50.3 | 54.2 | 59.5 | 62.8 | 54.6 | 54.6 |
| $R_{100-5000} - \text{ISO226-40Phon}$ | 68.5                   | 55.0 | 55.1 | 57.4 | 63.4 | 65.2 | 57.4 | 58.3 |
| $R_{100-5000} - \text{ISO226-30Phon}$ | 70.2                   | 55.3 | 57.3 | 58.9 | 65.2 | 66.3 | 58.5 | 60.1 |
| $R_{50-5000} - \text{ISO226-40Phon}$  | 65.0                   | 54.9 | 53.5 | 56.3 | 60.6 | 64.5 | 56.5 | 57.2 |
| $R_{50-5000} - \text{ISO226-30Phon}$  | 67.7                   | 55.3 | 56.0 | 58.1 | 63.1 | 65.9 | 58.0 | 59.3 |
| $R_{\text{living},85\%}$              | 56.1                   | 52.1 | 44.9 | 48.9 | 52.1 | 58.2 | 49.6 | 49.5 |

Note: a wide variety of descriptors can be defined using the A-weighting spectrum, however only  $R_{100-5000} - \text{dB(A)}$  is considered here to avoid redundancy. Indeed,  $R_{50-5000} - \text{dB(A)}$  and  $R_{50-3150} - \text{dB(A)}$  would have similar values as  $R_{\text{living}}$ , while  $R_{100-3150} - \text{dB(A)}$  would be very close to  $R_W + C_{100-3150}$ .



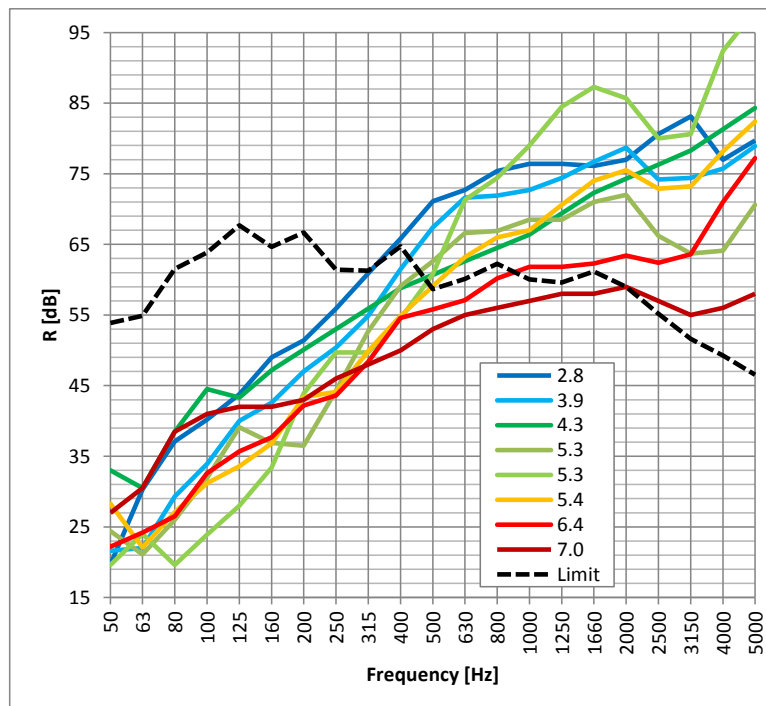
### 4.3 RESULTS

The average annoyance rating given by the test subjects to the different separating elements, considering all the sound sources, is represented together with their sound reduction indices in Figure 6, where high values of annoyance are represented in red and low values in blue.

From these results, it can be observed that low annoyance values correspond to sound reduction indices with important slopes and high values at medium and high frequencies (above 65 dB at 1 kHz), while high annoyance values correspond to sound reduction indices with smoother slopes and moderate values in the medium and high frequency range.

However, even though flanking transmission is not taken into account in this experiment, the sound pressure level in the listening room is not only determined by the source emission level and the wall sound reduction index. Indeed, the level of the audio stimuli can be lower than the background noise in the room, especially at high frequencies, as shown in Figure 1. Consequently, the ability to hear differences between the stimuli is limited above a certain frequency. The dashed black curve in Figure 6 represents the limit above which background noise is higher by at least 5 dB than the sound pressure level of the source, for any of the audio stimuli used in this part of the experiment. This shows that differences in the sound reduction indices above 500 Hz can hardly explain differences in the annoyance ratings obtained by the walls.

Remark: complementary tests were performed by increasing the level of all the sound stimuli by 5 dB, thus decreasing the influence of background noise. Results were not significantly affected.



**Figure 6: Separating elements classified by average annoyance**

A linear fit is performed between the average annoyance and the performance descriptors mentioned in section 3, considering all the separating walls and floors. Correlation coefficients are given in

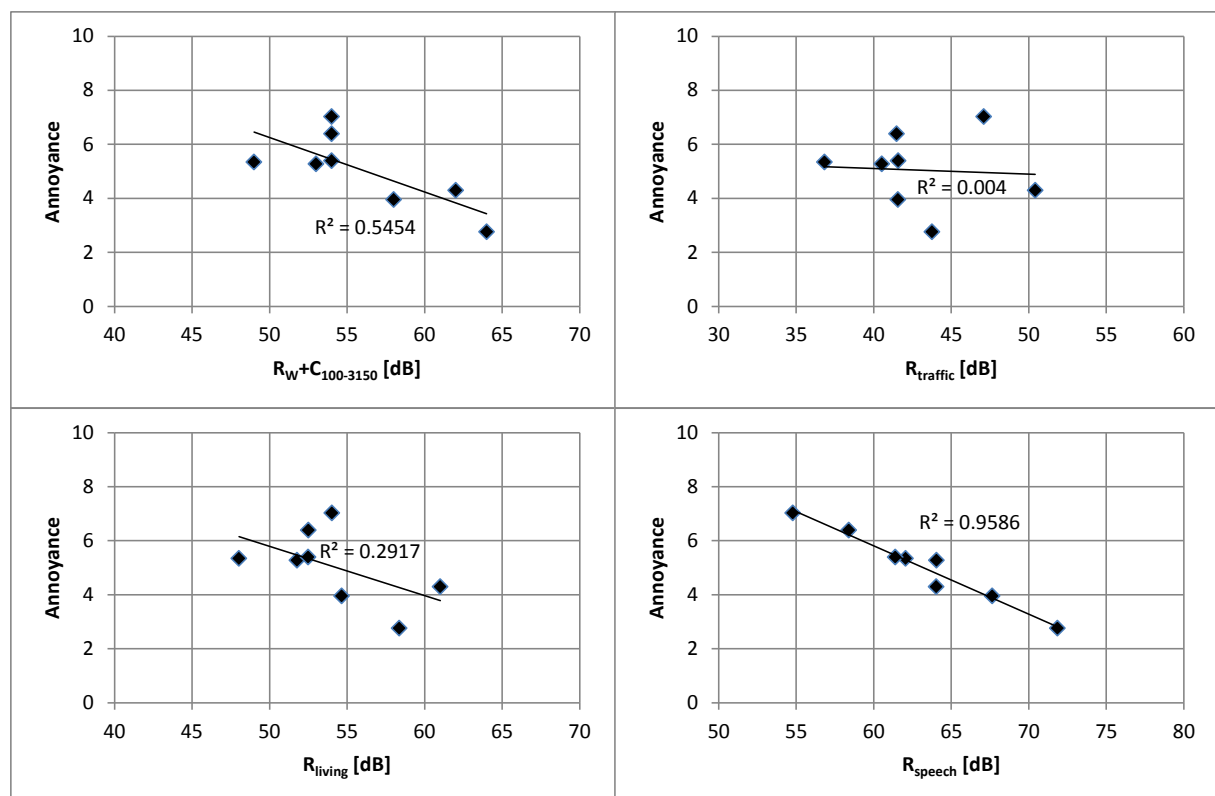
Table 5. All values that are lower or equal to -0.95 (which corresponds to  $R^2 \geq 0.9$ ) are highlighted in green. Some examples of linear fits are represented in Figure 7.

The sound source that is evaluated as the most annoying is rock music. For this source, all descriptors except  $R_{\text{traffic}}$  and  $R_{\text{speech}}$  are very well correlated to annoyance. For the other sound sources,  $R_{\text{traffic}}$ , which was designed for exterior noise, shows very poor correlation, while  $R_{\text{speech}}$  shows the best results.

On average, the descriptors based on the Phon curves defined in ISO 226 show rather good correlations as well. However, no improvement is obtained by starting the evaluation at 50 Hz instead of 100 Hz, except for the rock music sound source.

The descriptor currently used for interior noise  $R_W + C_{100-3150}$  does not appear to be very well correlated to annoyance, but the new proposed quantity  $R_{\text{living}}$  does not show better results. Very little difference is observed with  $R_{\text{living},85\%}$ .

These results are close to those obtained by Hongisto et al. in Finland [16].



**Figure 7: Relationship between performance descriptors and average annoyance - Interior noise (all sources)**

**Table 5: Correlation coefficients (R) between performance descriptors and annoyance – Interior noise**

|                                          | <i>Rock music</i> | <i>TV</i> | <i>Birthday party</i> | <i>House warming party</i> | <i>Home cinema</i> | <i>Classical music</i> | <b>All sources</b> |
|------------------------------------------|-------------------|-----------|-----------------------|----------------------------|--------------------|------------------------|--------------------|
| R <sub>living</sub>                      | -0.92             | -0.48     | -0.26                 | -0.55                      | -0.59              | -0.37                  | <b>-0.54</b>       |
| R <sub>traffic</sub>                     | -0.60             | 0.00      | 0.22                  | -0.07                      | -0.12              | 0.11                   | <b>-0.06</b>       |
| R <sub>speech</sub>                      | -0.74             | -0.97     | -0.96                 | -0.98                      | -0.96              | -0.97                  | <b>-0.98</b>       |
| R <sub>W</sub> +C <sub>100-3150</sub>    | -0.98             | -0.69     | -0.49                 | -0.75                      | -0.78              | -0.58                  | <b>-0.74</b>       |
| R <sub>W</sub> +C <sub>tr,100-3150</sub> | -0.93             | -0.52     | -0.30                 | -0.58                      | -0.60              | -0.40                  | <b>-0.57</b>       |
| R <sub>W</sub>                           | -0.99             | -0.85     | -0.69                 | -0.88                      | -0.89              | -0.76                  | <b>-0.88</b>       |
| R <sub>100-5000</sub> - dB(A)            | -0.99             | -0.73     | -0.54                 | -0.78                      | -0.80              | -0.63                  | <b>-0.78</b>       |
| R <sub>100-5000</sub> - ISO226-40Phon    | -0.97             | -0.87     | -0.73                 | -0.90                      | -0.92              | -0.80                  | <b>-0.90</b>       |
| R <sub>100-5000</sub> - ISO226-30Phon    | -0.94             | -0.91     | -0.79                 | -0.94                      | -0.95              | -0.85                  | <b>-0.94</b>       |
| R <sub>50-5000</sub> - ISO226-40Phon     | -0.98             | -0.77     | -0.61                 | -0.83                      | -0.86              | -0.69                  | <b>-0.82</b>       |
| R <sub>50-5000</sub> - ISO226-30Phon     | -0.96             | -0.85     | -0.72                 | -0.90                      | -0.92              | -0.79                  | <b>-0.90</b>       |
| R <sub>living,85%</sub>                  | -0.91             | -0.46     | -0.23                 | -0.52                      | -0.56              | -0.34                  | <b>-0.52</b>       |

## 5. LISTENING TESTS ON OUTDOOR AIRBORNE NOISE

### 5.1 SELECTED SOUND SOURCES AND LEVEL SETTING

The 7 exterior noise sources listed in Table 6 were selected because they were representative of what building occupants complain most.

To keep the test duration within reasonable limits, only a certain part of the initial sound samples had sometimes to be selected. The spectra of the initial sound samples (before time selection and filtering) corresponding to each of the selected sound sources are given in Annexe 4. Other sources were available but were not selected, since their spectra were not significantly different.

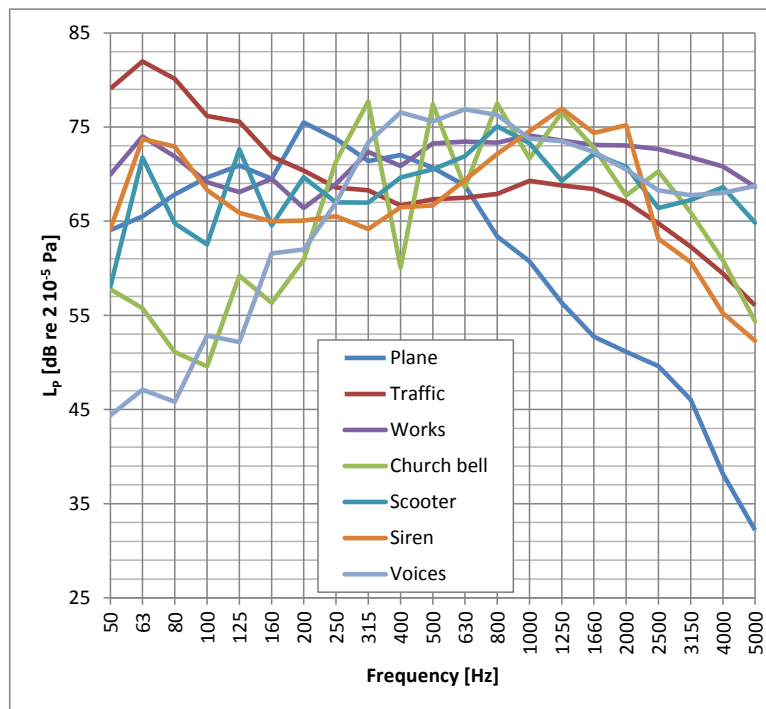
**Table 6: Selected sources of exterior noise**

| Source No. | Source type                                               | Duration [s] | $L_{eq}$ [dB] | $L_{Aeq}$ [dB(A)] |
|------------|-----------------------------------------------------------|--------------|---------------|-------------------|
| 1          | Pass-by of a plane                                        | 38           | 81            | 74                |
| 2          | Traffic in a busy street                                  | 19           | 86            | 77                |
| 3          | Construction works (with equipment noise and loud voices) | 24           | 85            | 83                |
| 4          | Church bell ringing                                       | 19           | 84            | 83                |
| 5          | Loud voices                                               | 19           | 82            | 81                |
| 6          | Pass-by of a scooter                                      | 5            | 83            | 82                |
| 7          | Pass-by of an ambulance (with siren on)                   | 10           | 84            | 83                |

Before being filtered with the sound reduction index of the façade walls, different values of volume gain are applied to the sound samples so that a realistic balance is found between them.

Then a second equalization step is performed on the traffic sound sample for each of the different façade walls in order to get a resulting sound pressure level in the reception room (after filtering with the sound reduction index) around 30 dB(A). Indeed, according to the French acoustic regulation, façades must be dimensioned based on the exterior noise level due to ground transportation. With a proper dimensioning, buildings that are strongly exposed to traffic noise should have better performing façades and, as a result, the interior noise level should always be approximately the same. The same correction is finally applied to the other sound sources, which implies that the levels of the different sources are all linked to that of traffic noise. The assumption is made that the distance between the building and the sound sources can vary (multiplication by a given factor, identical for all sources), and that the type of façade wall is chosen such that the sound pressure level inside the building remains the same. As a result, the difference in emission levels reaches 17 dB between the best performing and the worst performing façades. This corresponds to a multiplication of the source-building distance by a factor of 7.

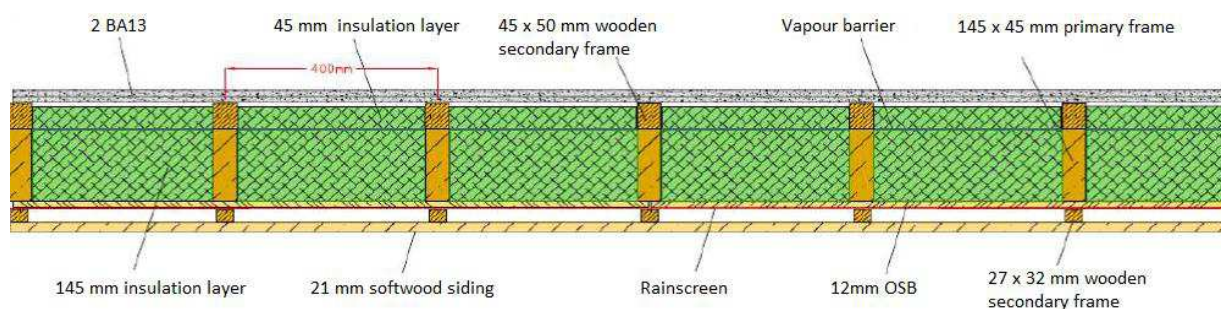
The highest emission levels (i.e. for the best performing façade) of the 7 sound sources are represented in Figure 8.



**Figure 8: Emission spectra of the selected exterior noise sources**

## 5.2 SELECTED FAÇADE WALLS

In this part of the test, sound samples are filtered with the sound reduction index of the 10 following separating walls and floors. The dimension of the walls is 4x2.5 m<sup>2</sup> and that of the windows is 1.4x1.2 m<sup>2</sup>. The lightweight façade element is described in Figure 9.

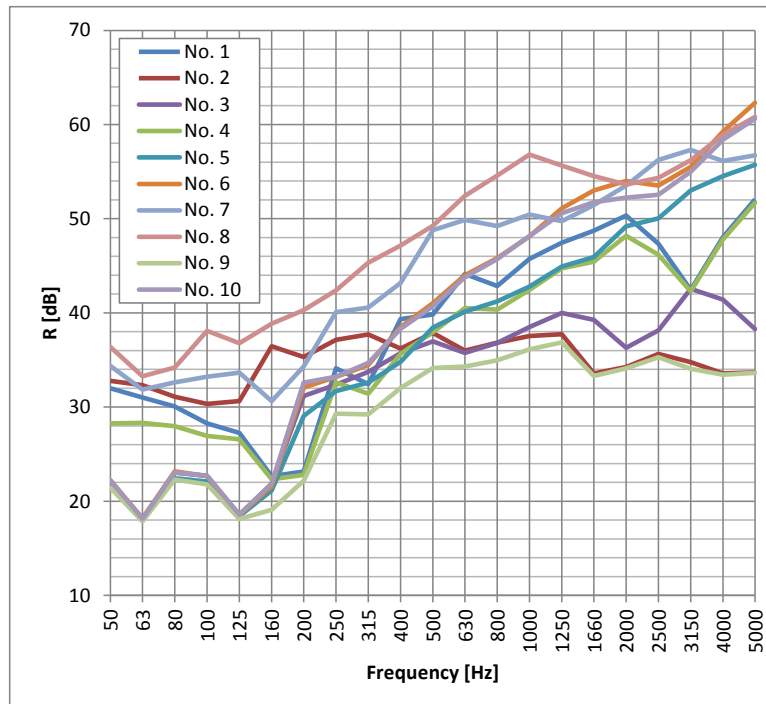


**Figure 9: Description of the lightweight façade element**

**Table 7: Selected façade walls**

| Façade wall No. | Description                                                                                                                                                                    |
|-----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1               | 16 cm thick concrete wall and associated thermal insulation with $R_W+C_{tr}=48$ dB + double pane window with $R_W+C_{tr}=28$ dB                                               |
| 2               | 16 cm thick concrete wall and associated thermal insulation with $R_W+C_{tr}=48$ dB + double pane window with $R_W+C_{tr}=43$ dB + air inlet with $D_{ne,w}+C_{tr}=36$ dB      |
| 3               | Lightweight wall with $R_W+C_{tr}=35$ dB + double pane window with $R_W+C_{tr}=43$ dB + air inlet with $D_{ne,w}+C_{tr}=39$ dB                                                 |
| 4               | 16 cm thick concrete wall and associated thermal insulation with $R_W+C_{tr}=48$ dB + double pane window with $R_W+C_{tr}=28$ dB + roller shutter with $D_{ne,w}+C_{tr}=41$ dB |
| 5               | Lightweight wall with $R_W+C_{tr}=35$ dB + double pane window with $R_W+C_{tr}=36$ dB + roller shutter with $D_{ne,w}+C_{tr}=41$ dB                                            |
| 6               | Lightweight wall with $R_W+C_{tr}=35$ dB + double pane window with $R_W+C_{tr}=40$ dB                                                                                          |
| 7               | 20 cm thick hollow concrete blocks and associated thermal insulation with $R_W+C_{tr}=51$ dB + double pane window with $R_W+C_{tr}=36$ dB                                      |
| 8               | 20 cm thick hollow concrete blocks and associated thermal insulation with $R_W+C_{tr}=51$ dB + double pane window with $R_W+C_{tr}=43$ dB                                      |
| 9               | Lightweight wall with $R_W+C_{tr}=35$ dB + double pane window with $R_W+C_{tr}=28$ dB + air inlet with $D_{ne,w}+C_{tr}=36$ dB + roller shutter with $D_{ne,w}+C_{tr}=41$ dB   |
| 10              | Lightweight wall with $R_W+C_{tr}=35$ dB + double pane window with $R_W+C_{tr}=43$ dB                                                                                          |

These walls have very different acoustic performances, as shown in Figure 10. Table 8 summarizes their Single Number Ratings.



**Figure 10: Acoustic performance of the selected façade walls**

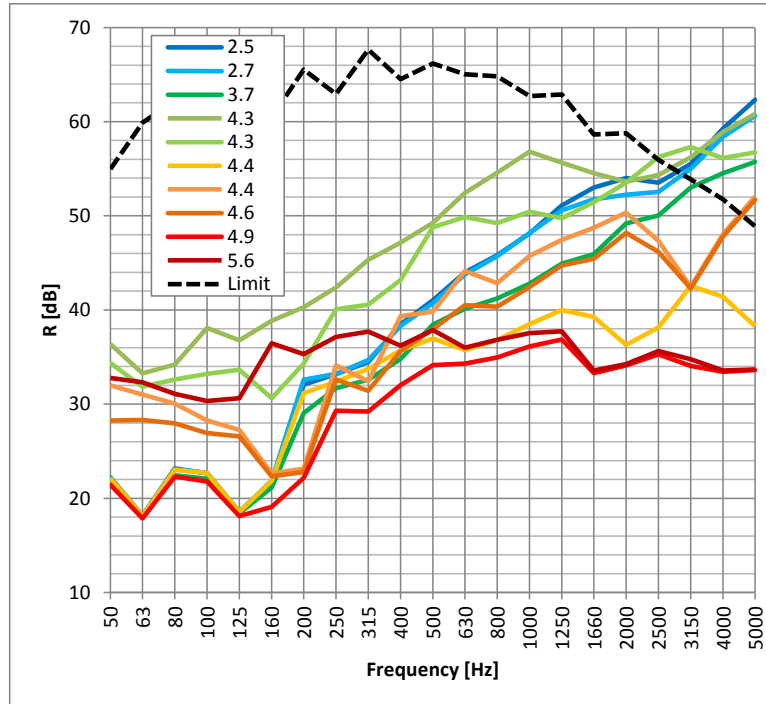
**Table 8: Single Number Ratings of the selected façade walls**

|                                          | <i>Façade wall No.</i> |      |      |      |      |      |      |      |      |      |
|------------------------------------------|------------------------|------|------|------|------|------|------|------|------|------|
|                                          | 1                      | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
| R <sub>living</sub>                      | 40.0                   | 35.1 | 36.5 | 39.0 | 38.8 | 40.2 | 47.8 | 51.9 | 32.9 | 40.3 |
| R <sub>traffic</sub>                     | 34.9                   | 35.4 | 31.9 | 34.0 | 32.1 | 33.0 | 42.4 | 46.7 | 29.5 | 33.0 |
| R <sub>speech</sub>                      | 42.9                   | 36.0 | 37.5 | 40.4 | 40.6 | 44.2 | 48.8 | 52.0 | 34.3 | 44.0 |
| R <sub>W</sub> +C <sub>100-3150</sub>    | 39.0                   | 36.0 | 36.0 | 38.0 | 38.0 | 39.0 | 47.0 | 51.0 | 33.0 | 40.0 |
| R <sub>W</sub> +C <sub>tr,100-3150</sub> | 35.0                   | 36.0 | 33.0 | 34.0 | 33.0 | 34.0 | 43.0 | 48.0 | 30.0 | 34.0 |
| R <sub>W</sub>                           | 42                     | 36   | 37   | 40   | 40   | 43   | 49   | 52   | 34   | 43   |
| R <sub>100-5000</sub> - dB(A)            | 40.1                   | 35.1 | 36.6 | 39.0 | 39.1 | 40.6 | 47.9 | 52.0 | 32.9 | 40.6 |
| R <sub>100-5000</sub> - ISO226-40Phon    | 41.8                   | 35.1 | 37.8 | 40.6 | 41.6 | 43.7 | 49.9 | 53.2 | 33.6 | 43.8 |
| R <sub>100-5000</sub> - ISO226-30Phon    | 42.6                   | 35.0 | 38.2 | 41.4 | 42.7 | 45.2 | 50.7 | 53.8 | 33.8 | 45.1 |
| R <sub>50-5000</sub> - ISO226-40Phon     | 41.8                   | 35.1 | 37.8 | 40.6 | 41.5 | 43.6 | 49.8 | 53.2 | 33.6 | 43.6 |
| R <sub>50-5000</sub> - ISO226-30Phon     | 42.6                   | 35.0 | 38.2 | 41.4 | 42.7 | 45.1 | 50.7 | 53.7 | 33.8 | 45.1 |
| R <sub>living,85%</sub>                  | 37.2                   | 35.6 | 34.8 | 36.2 | 35.8 | 37.0 | 45.1 | 49.5 | 31.6 | 37.1 |

### 5.3 RESULTS

The average annoyance rating given by the test subjects to the different façade walls, considering all the sound sources, is represented together with their sound reduction indices in Figure 11, where high values of annoyance are represented in red and low values in blue.

The dashed black line represents the limit above which background noise is higher by at least 5 dB than the sound pressure level of the source, for any of the audio stimuli used in this part of the experiment (see section 4.3 for more details). This shows that the influence of background noise on the test results is limited.



**Figure 11: Façade walls classified by average annoyance**

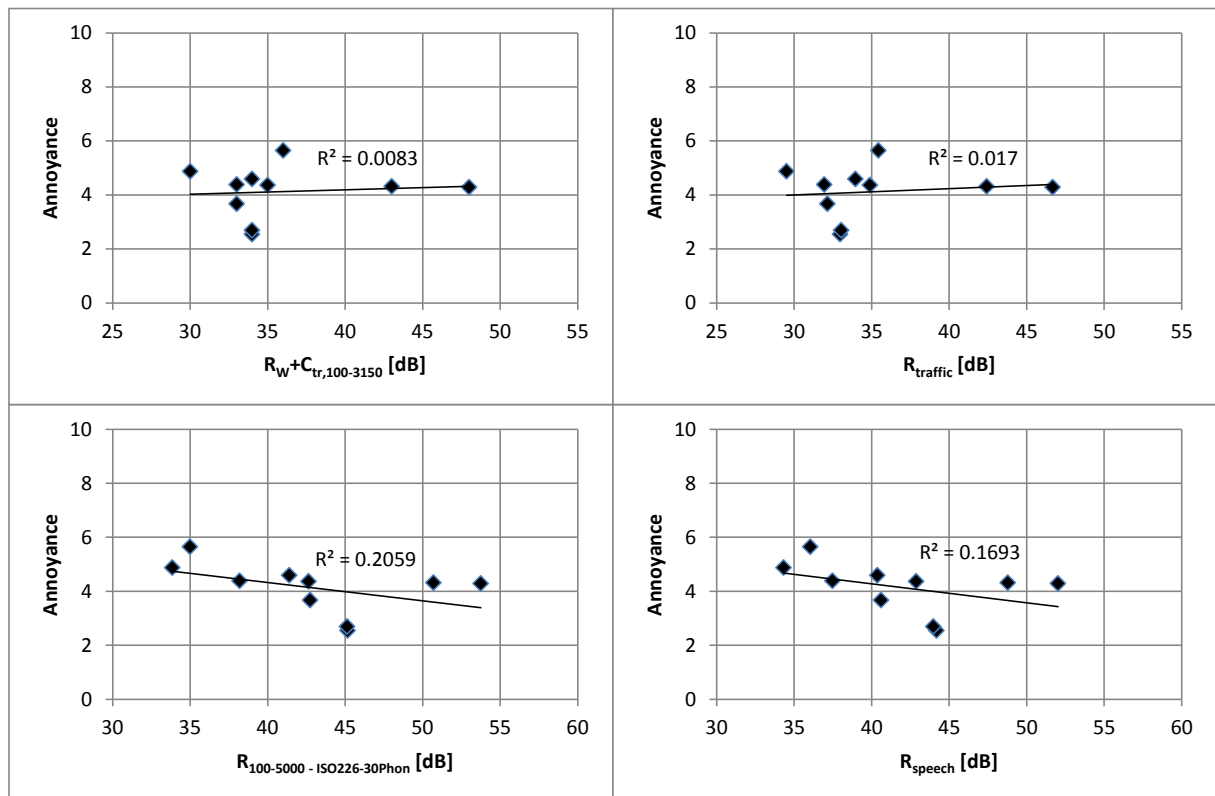
A linear fit is performed between the average annoyance and the performance descriptors mentioned in section 3, considering all the façade walls. Correlation coefficients are given in Table 9. The best correlation for each sound source is highlighted in green. Some examples of linear fits are represented in Figure 12.

The sound source that is evaluated as the most annoying is people talking in the street. For this source, none of the descriptors listed in section 3 is well correlated to annoyance. Results are similar for the other sound sources and on average.

All descriptors are poorly correlated to annoyance, some of them even having positive correlation coefficients, which means that the higher the performance value, the higher the annoyance. This is the case for the descriptor currently used for exterior noise,  $R_W + C_{tr,100-3150}$ , and for the proposed new descriptor  $R_{traffic}$ . Moreover, the worst correlation values observed concern the road traffic stimuli, despite the fact that these two indices were designed for this sound source.

The method proposed to set the emission levels of the sound sources is probably the cause of these bad correlations. Indeed, when comparing two different façades, two parameters are modified: the sound reduction index of the building element and the level of the sound sources. This undoubtedly introduces a bias, compared to the part of the test that deals with indoor noise, where only the acoustic performance of the wall or floor was modified.





**Figure 12: Relationship between performance descriptors and average annoyance - Exterior noise (all sources)**

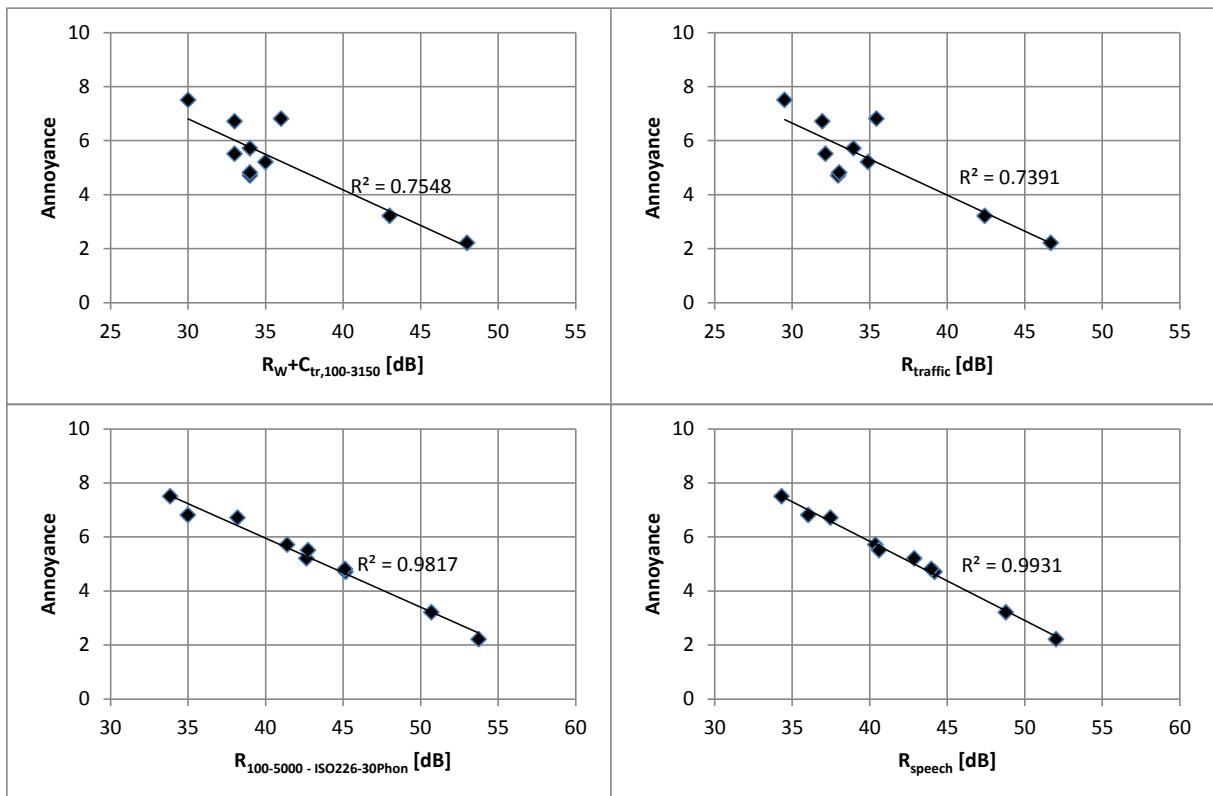
**Table 9: Correlation coefficients (R) between performance descriptors and annoyance – Exterior noise**

|                                        | Plane | Traffic | Works | Church bells | Voices | Scooter | Siren | <b>All sources</b> |
|----------------------------------------|-------|---------|-------|--------------|--------|---------|-------|--------------------|
| R <sub>living</sub>                    | -0.18 | -0.12   | -0.28 | -0.26        | -0.20  | -0.15   | -0.30 | <b>-0.23</b>       |
| R <sub>traffic</sub>                   | 0.11  | 0.17    | 0.05  | 0.12         | 0.16   | 0.21    | 0.06  | <b>0.13</b>        |
| R <sub>speech</sub>                    | -0.31 | -0.32   | -0.46 | -0.43        | -0.38  | -0.33   | -0.49 | <b>-0.41</b>       |
| R <sub>W+C<sub>100-3150</sub></sub>    | -0.16 | -0.08   | -0.23 | -0.20        | -0.14  | -0.10   | -0.24 | <b>-0.17</b>       |
| R <sub>W+C<sub>tr,100-3150</sub></sub> | 0.05  | 0.13    | 0.01  | 0.08         | 0.12   | 0.17    | 0.04  | <b>0.09</b>        |
| R <sub>W</sub>                         | -0.27 | -0.25   | -0.39 | -0.37        | -0.32  | -0.26   | -0.42 | <b>-0.35</b>       |
| R <sub>100-5000 - dB(A)</sub>          | -0.21 | -0.14   | -0.30 | -0.28        | -0.22  | -0.17   | -0.31 | <b>-0.25</b>       |
| R <sub>100-5000 - ISO226-40Phon</sub>  | -0.32 | -0.28   | -0.43 | -0.43        | -0.37  | -0.32   | -0.46 | <b>-0.40</b>       |
| R <sub>100-5000 - ISO226-30Phon</sub>  | -0.37 | -0.33   | -0.49 | -0.48        | -0.43  | -0.38   | -0.51 | <b>-0.45</b>       |
| R <sub>50-5000 - ISO226-40Phon</sub>   | -0.32 | -0.27   | -0.43 | -0.42        | -0.37  | -0.32   | -0.45 | <b>-0.39</b>       |
| R <sub>50-5000 - ISO226-30Phon</sub>   | -0.36 | -0.33   | -0.48 | -0.48        | -0.43  | -0.38   | -0.51 | <b>-0.45</b>       |
| R <sub>living,85%</sub>                | -0.08 | 0.00    | -0.14 | -0.10        | -0.05  | 0.00    | -0.13 | <b>-0.08</b>       |

## 5.4 ADDITIONAL TESTS

Further tests were carried out on 24 new participants. The same method used for interior noise was followed to produce new stimuli in which the “emission level” of each sound source is fixed. Consequently, the sound pressure level in the listening room directly depends on the performance of the façade. Results of these additional tests are given in Table 10. All correlation coefficient values that are lower or equal to -0.95 (which corresponds to  $R^2 \geq 0.9$ ) are highlighted in green. Some examples of linear fits are represented in Figure 13.

These results show very good correlations between most descriptors and annoyance. The worst – but still acceptable – correlations correspond to  $R_{W+C_{tr,100-3150}}$  and  $R_{traffic}$ , without any significant difference between them. It can also be noticed that these two descriptors behave better for sound sources that have a strong low frequency content than for sources with a rather medium or high frequency spectrum such as church bells, voices or sirens for example.



**Figure 13: Relationship between performance descriptors and average annoyance - Exterior noise (all sources; additional tests)**

**Table 10: Correlation coefficients (R) between performance descriptors and annoyance – Exterior noise (additional tests)**

|                                       | Plane | Traffic | Works | Church bells | Voices | Scooter | Siren | All sources |
|---------------------------------------|-------|---------|-------|--------------|--------|---------|-------|-------------|
| $R_{\text{living}}$                   | -0.96 | -0.98   | -0.98 | -0.95        | -0.94  | -0.96   | -0.90 | -0.97       |
| $R_{\text{traffic}}$                  | -0.95 | -0.94   | -0.86 | -0.80        | -0.78  | -0.83   | -0.73 | -0.86       |
| $R_{\text{speech}}$                   | -0.93 | -0.97   | -0.99 | -0.99        | -0.99  | -1.00   | -0.98 | -1.00       |
| $R_W + C_{100-3150}$                  | -0.98 | -0.99   | -0.97 | -0.94        | -0.92  | -0.96   | -0.89 | -0.97       |
| $R_W + C_{\text{tr},100-3150}$        | -0.97 | -0.94   | -0.86 | -0.81        | -0.79  | -0.84   | -0.74 | -0.87       |
| $R_W$                                 | -0.95 | -0.98   | -0.99 | -0.99        | -0.98  | -0.99   | -0.96 | -1.00       |
| $R_{100-5000} - \text{dB(A)}$         | -0.96 | -0.98   | -0.99 | -0.97        | -0.96  | -0.98   | -0.92 | -0.99       |
| $R_{100-5000} - \text{ISO226-40Phon}$ | -0.92 | -0.96   | -0.99 | -0.99        | -0.99  | -0.99   | -0.96 | -0.99       |
| $R_{100-5000} - \text{ISO226-30Phon}$ | -0.91 | -0.95   | -0.99 | -0.99        | -0.99  | -0.99   | -0.97 | -0.99       |
| $R_{50-5000} - \text{ISO226-40Phon}$  | -0.92 | -0.96   | -0.99 | -0.99        | -0.99  | -0.99   | -0.96 | -0.99       |
| $R_{50-5000} - \text{ISO226-30Phon}$  | -0.91 | -0.95   | -0.99 | -0.99        | -0.99  | -0.99   | -0.97 | -0.99       |
| $R_{\text{living},85\%}$              | -0.98 | -0.97   | -0.93 | -0.89        | -0.87  | -0.91   | -0.82 | -0.93       |

## CONCLUSION

In this work, listening test experiments were conducted on 26 people to evaluate the correlation between performance descriptors and annoyance produced by the exposure to airborne noise from outside an apartment building and from the neighbors. Building systems commonly used in France were considered, as well as realistic sound sources.

Results show that the performance descriptors currently used in the French acoustic regulation are moderately correlated to annoyance for interior noise. It can also be seen that taking the low frequency range (third octave bands 50 to 80 Hz) into account in the evaluation of the performance indices does not lead to a better correlation. Consequently, the new index proposed in ISO/CD 16717,  $R_{\text{living}}$ , does not give better correlations than the current descriptor. However, other descriptors like  $R_{\text{speech}}$  and the indices that use a frequency weighting based on the Phon curves defined in ISO 226 seem to give better results on average.

The results obtained for interior noise follow the conclusions of a similar study recently conducted in Finland [16].

However, these results must be taken carefully because of some remaining interrogations about the test methodology. In particular, all the sound stimuli used in the experiment were produced using a high-pass filter from third octave band 50 Hz. The influence of lower – but still audible – frequencies should then be investigated, as some daily life sound sources have a strong low frequency content. An extension of this work with sound reproduction down to 20 Hz could be considered. However, the acoustic performance of building elements is never measured at these frequencies. Extrapolation is then required, for example following the method proposed by Mortensen [3], that extends the value of the sound reduction index obtained at 50 Hz to lower frequencies.

For exterior noise, poor correlations are observed with the first series of tests, probably due to a biased method for the production of the audio stimuli. Indeed, the choice was made to maintain constant sound levels in the listening room, considering the fact that the acoustic conception of buildings is based on their exposure level to outdoor noise sources. Changing the façade is represented in the experiment by a modification of its sound reduction index, but also by a modification of the source emission level. Additional tests were performed by modifying only the performance of the façade wall. Results are more comparable to those obtained for interior noise with strong correlation values. They also suggest that the new index proposed in ISO/CD 16717  $R_{\text{traffic}}$  is not better correlated to annoyance than the current descriptor.

Due to time limitation, this study was restricted to airborne noise. Further work is also considered to extend the method to annoyance related to impact noise. The main difficulty will then be the production of the sound stimuli, which at the same time requires a significant amount of different configurations and recording conditions that are rarely found in an acoustics lab.

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## **ANNEXES**

## ANNEXE 1 : PICTURES OF THE TEST ROOM





## ANNEXE 2 : QUESTIONNAIRE AND INSTRUCTIONS GIVEN TO THE TEST PARTICIPANTS

V3 (2013-08-26)

ID 32

### Tests d'écoute

#### Questionnaire préliminaire

Merci de renseigner les champs suivants :

Age..... ☐ < 20 ☐ 20-29 ☐ 30-39 ☐ 40-49 ☐ 50-59 ☐ 60-69 ☐ ≥ 70

Sexe..... ☐ M ☐ F

Avez-vous, à votre connaissance, des troubles auditifs ?..... ☐ Oui ☐ Non

Vous habitez..... ☐ En zone urbaine ☐ En zone rurale

De quel type est votre logement ?..... ☐ Maison individuelle ☐ Appartement

☐ Maison accolée ☐ Autre

#### Instructions

Imaginez-vous en train de vous reposer dans votre appartement – fenêtres fermées – après une journée de travail.

13 séries d'extraits sonores vous seront présentées : bruits de la vie courante, provenant de l'extérieur du bâtiment ou des logements voisins. Vous devrez noter chaque extrait sonore en fonction de la gêne qu'il provoque chez vous, dans la situation fictive décrite plus haut. Une échelle de 0 (pas du tout gênant) à 10 (extrêmement gênant) est utilisée.

Au sein d'une même série, vous pourrez écouter chaque extrait sonore à volonté en cliquant sur le bouton  et ajuster les notes associées aux différents extraits grâce aux curseurs correspondants. Une note identique peut être attribuée à plusieurs extraits.

Remarque : même si certains extraits sonores sont peu audibles, merci de ne pas modifier le réglage du volume de l'ordinateur !

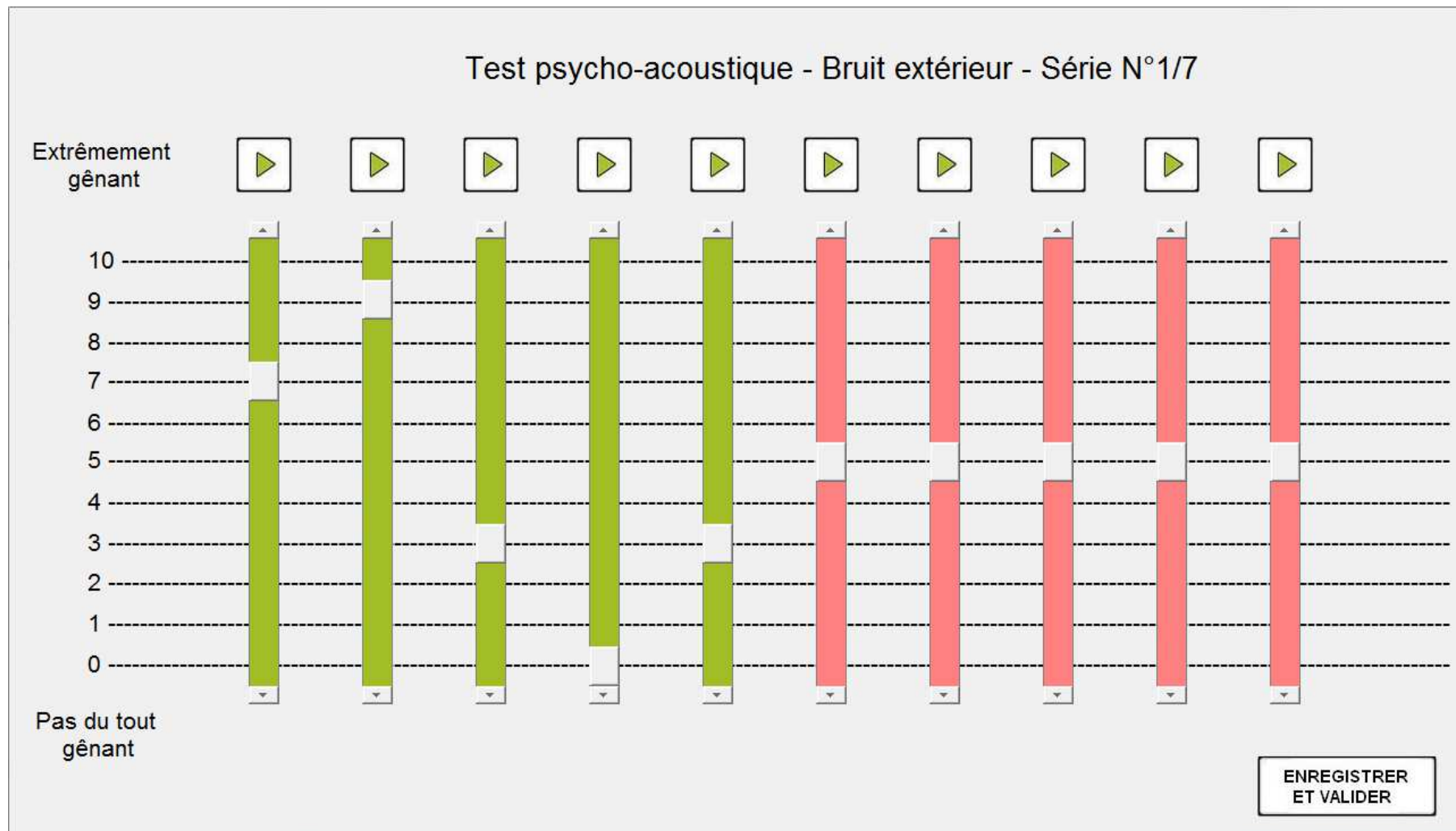
Une fois que tous les extraits d'une série ont été notés, validez votre réponse et passez à la série suivante en cliquant sur le bouton situé en bas à droite de l'écran.

Attention : lorsque vous validez vos réponses pour une série d'extraits, celles-ci ne peuvent plus être modifiées.

Lorsque vous aurez noté les 7 premières séries d'extraits sonores, attendez quelques secondes. Une nouvelle fenêtre apparaîtra et vous pourrez poursuivre avec les 6 dernières séries.

*Bon test et merci de votre participation !*

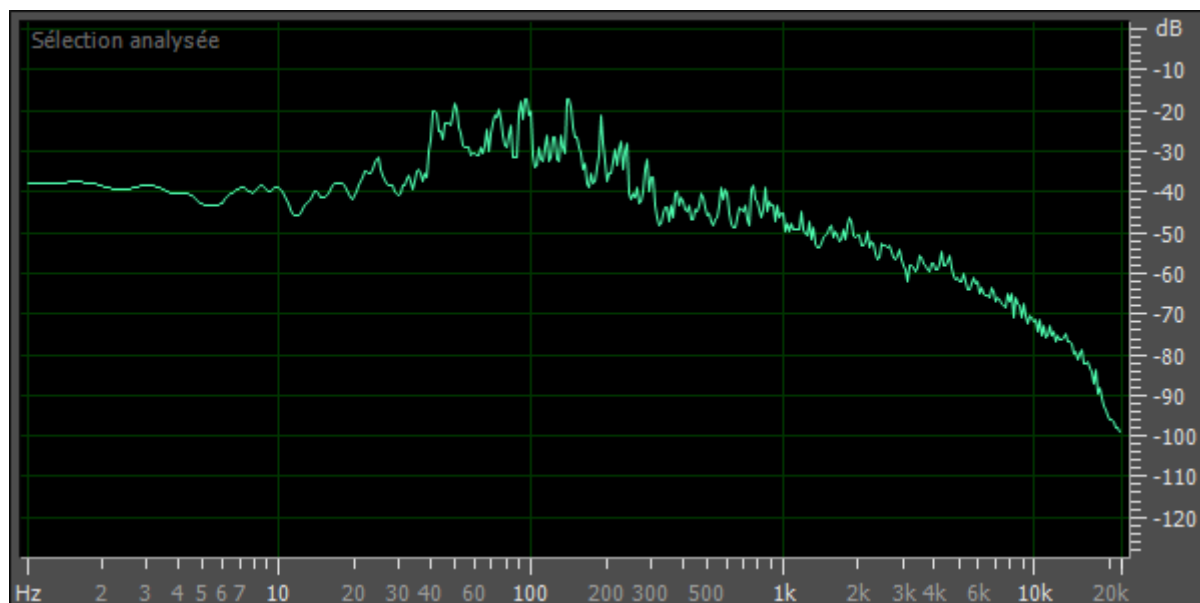
### ANNEXE 3 : GRAPHICAL USER INTERFACE DEVELOPED FOR THE LISTENING TESTS



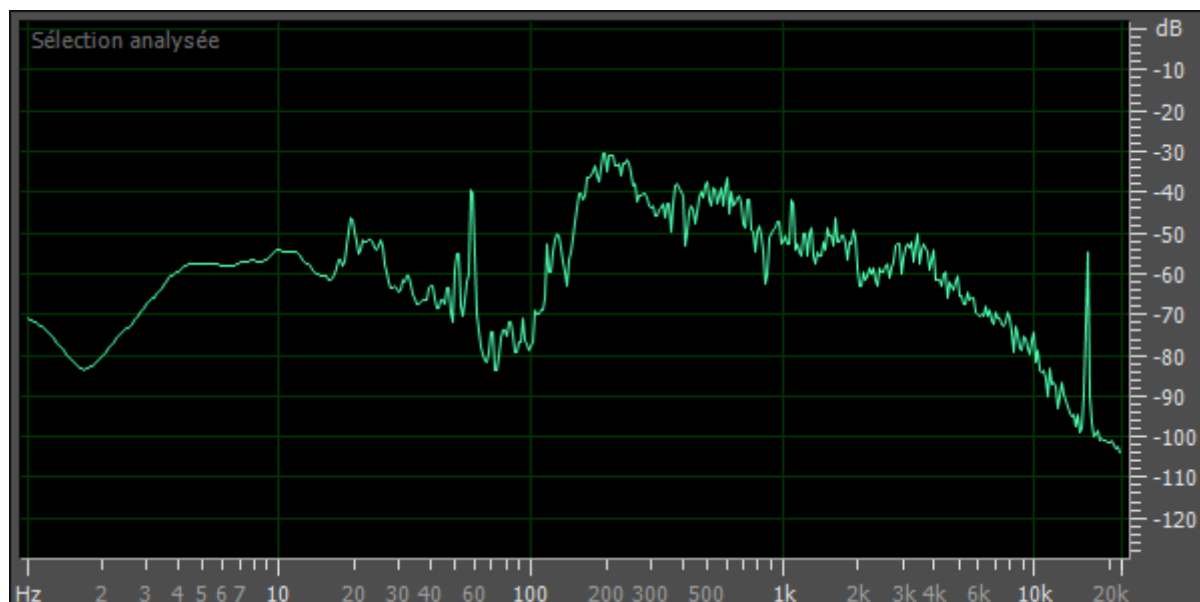
## ANNEXE 4 : EMISSION SPECTRA OF THE SOUND SOURCES USED IN THE TEST

### INTERIOR NOISE

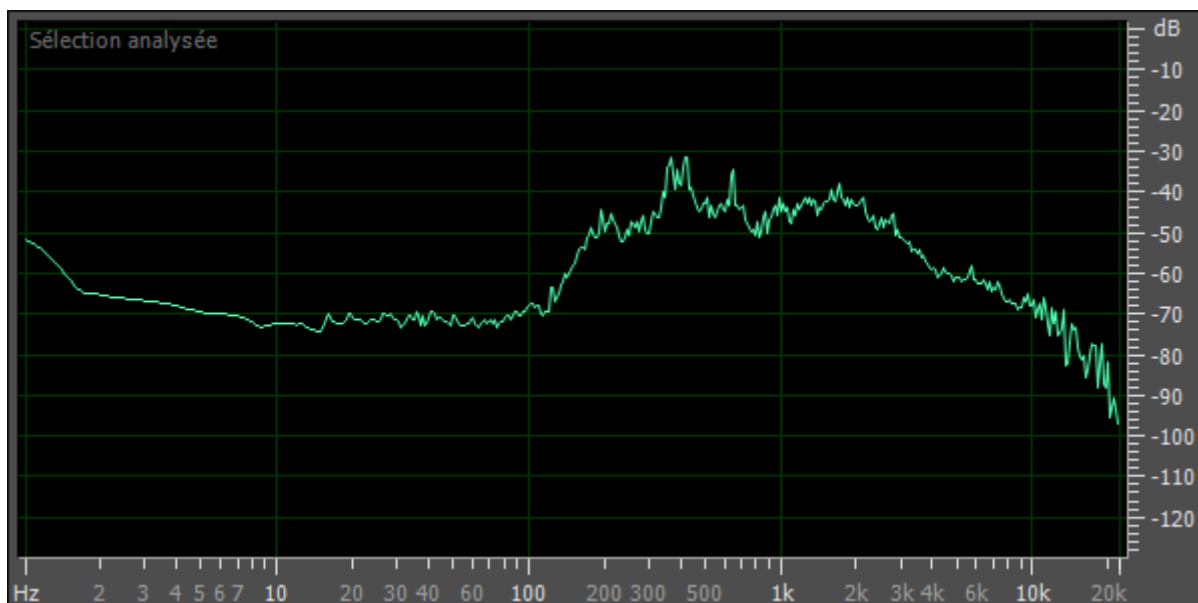
Rock music



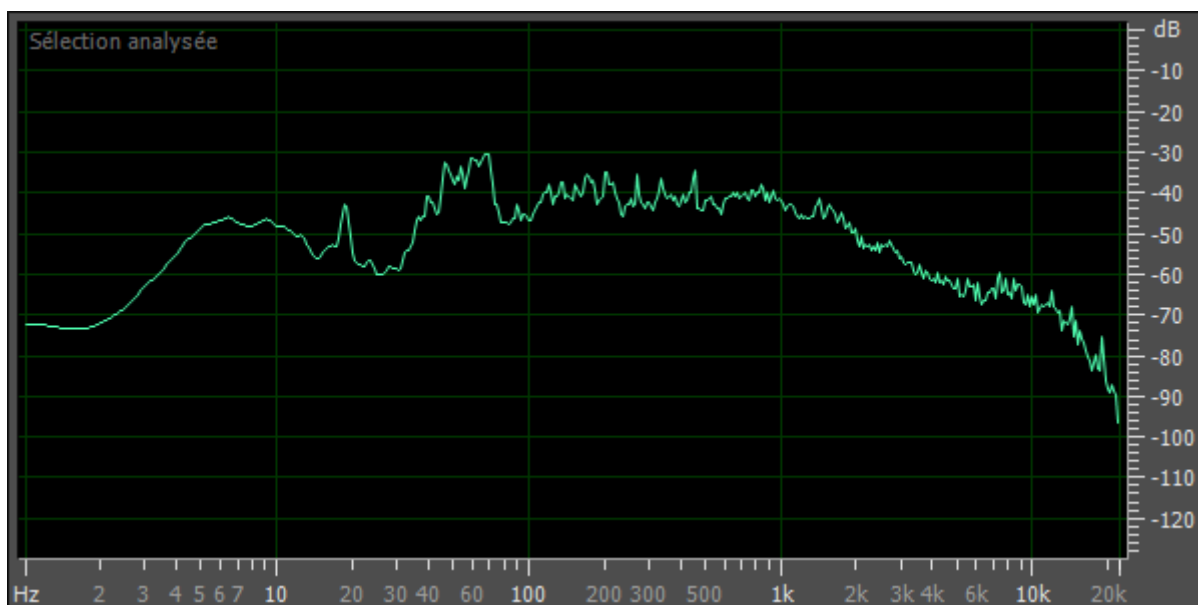
Television



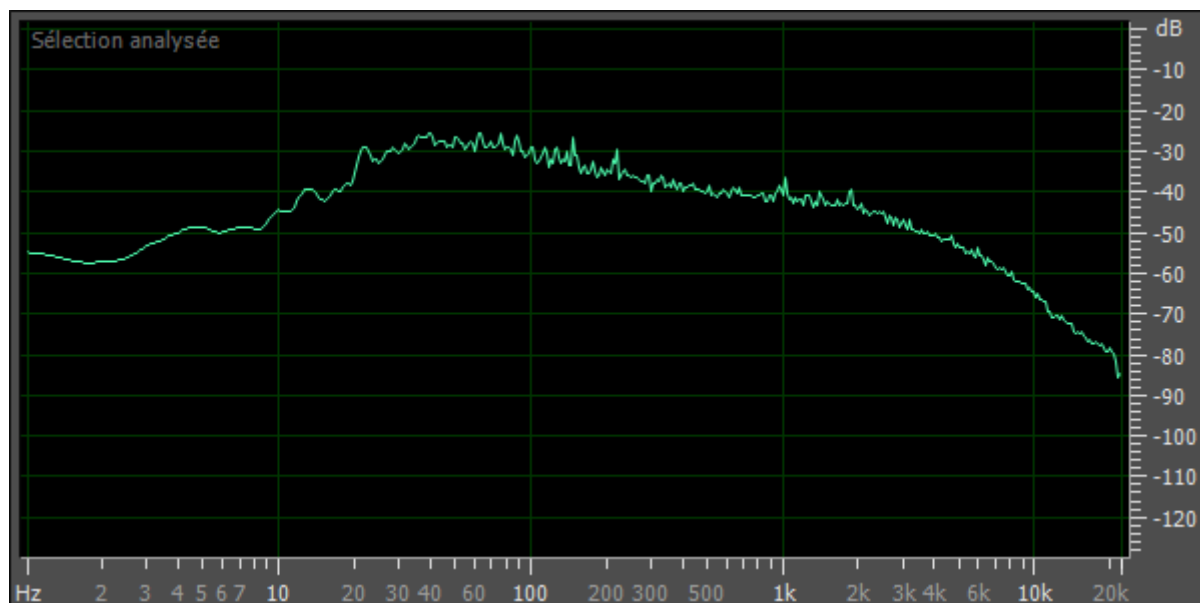
## Birthday party



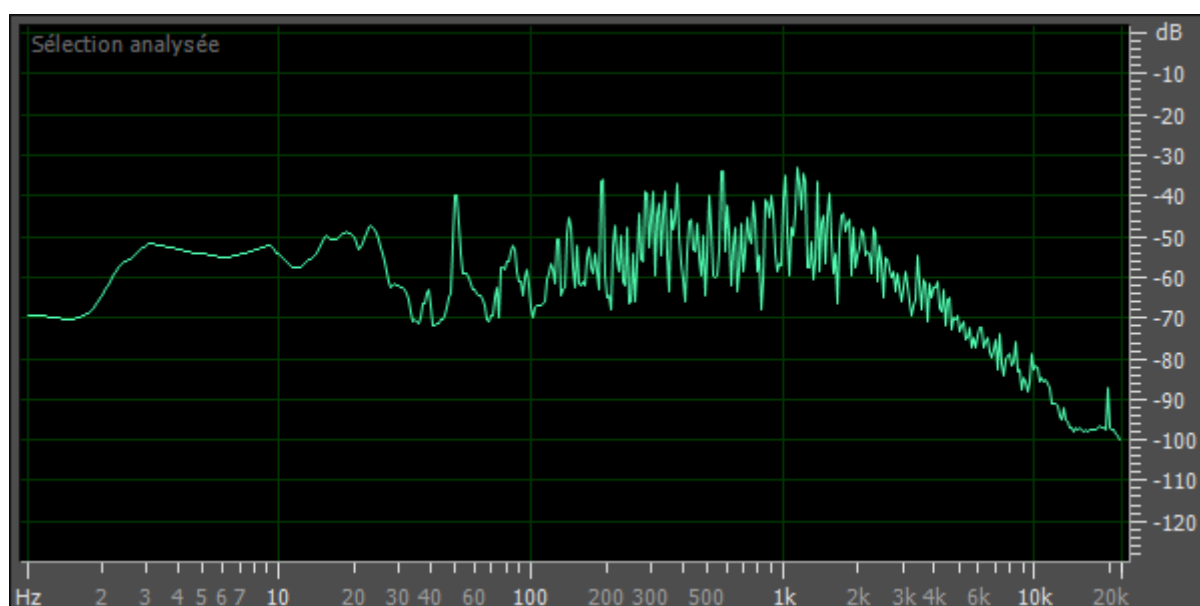
## House warming party



## Home cinema

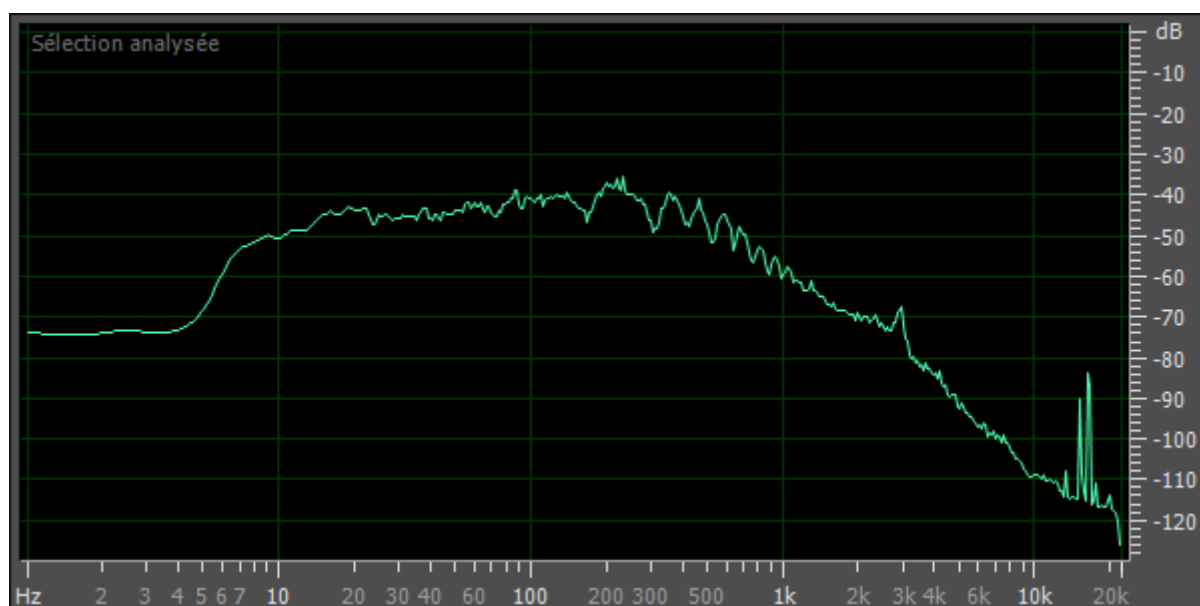


## Classical music

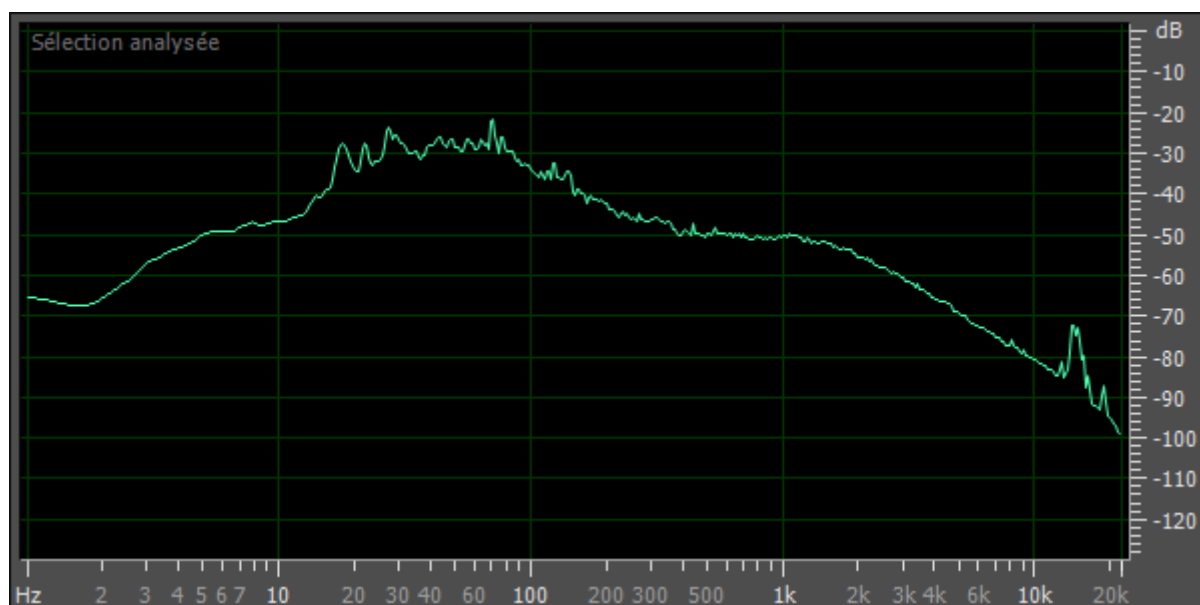


## EXTERIOR NOISE

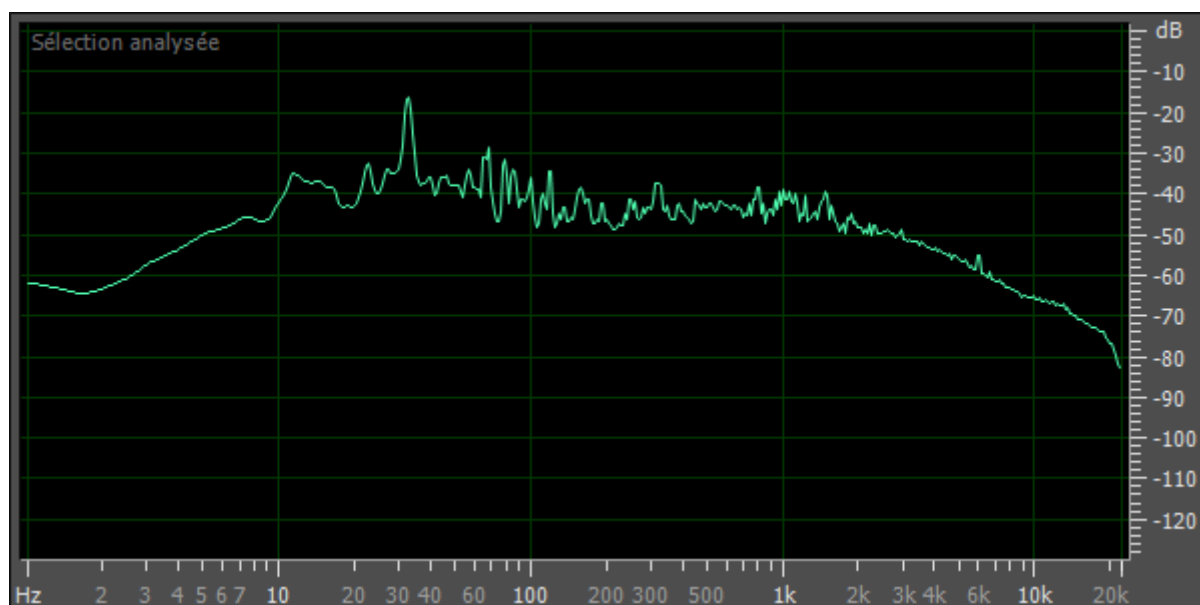
Plane



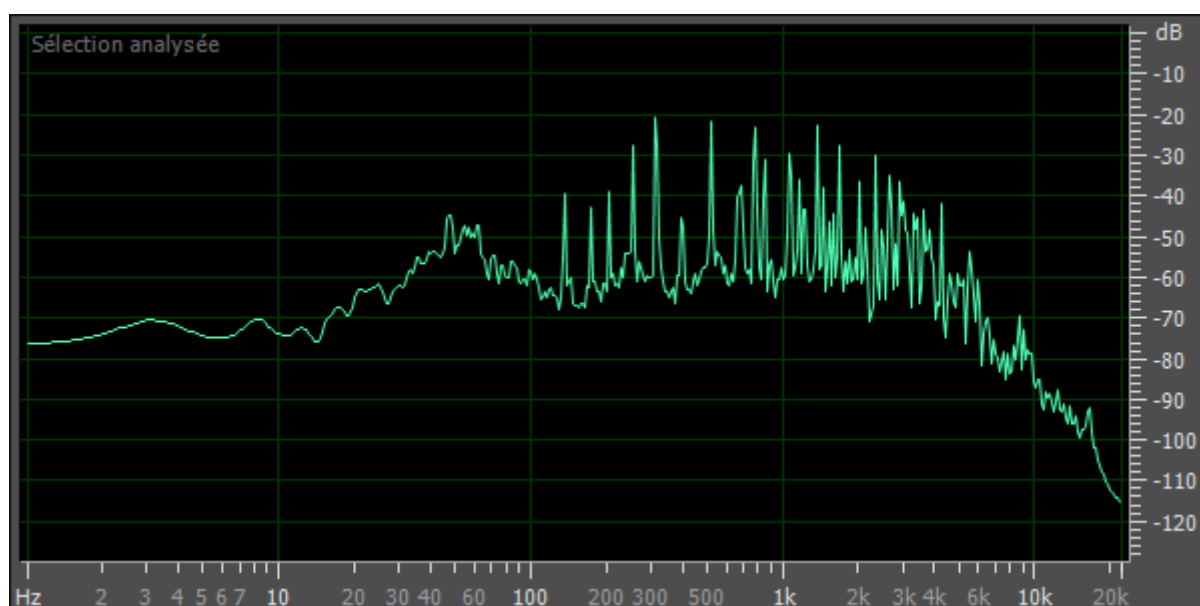
Traffic



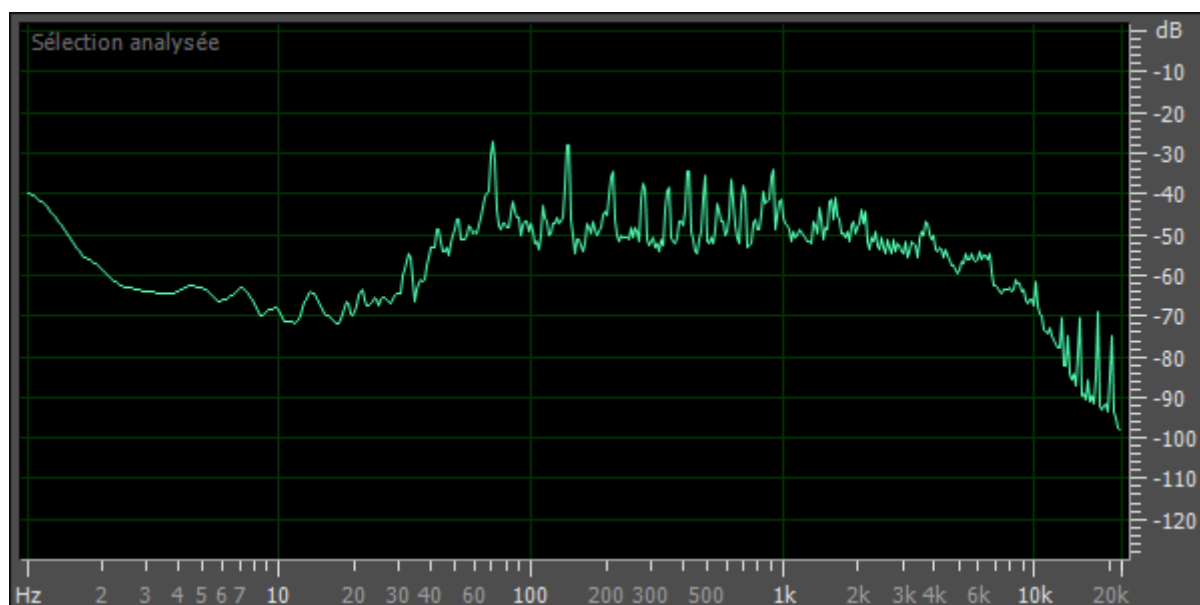
## Construction works



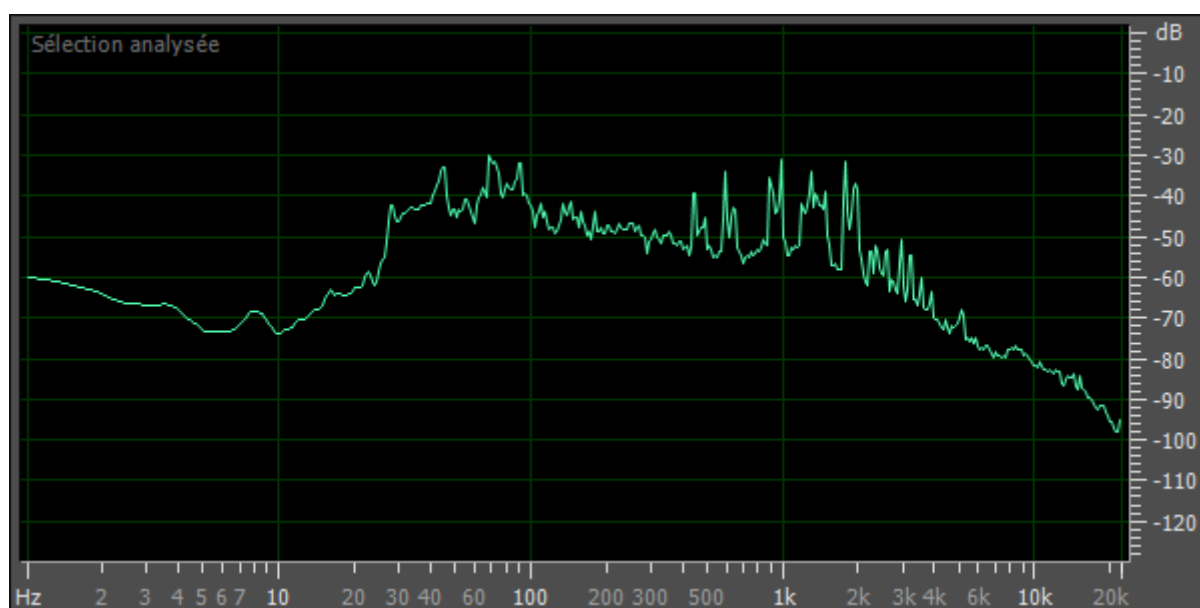
## Church bell



## Scooter

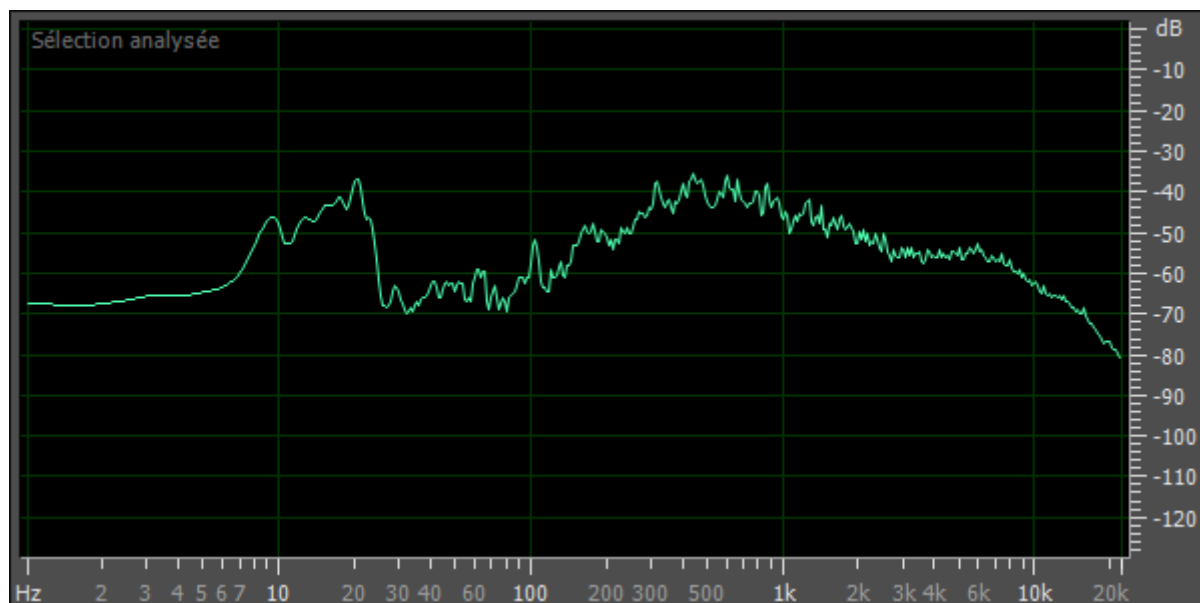


## Siren





## Voices



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