ON THE RELATION OF ROOM ACOUSTIC DIFFUSION OVER BINAURAL LOUDNESS

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Abstract

The evaluation of noise annoyance in indoor environments is a major concern in room acoustics. The characteristics of room surfaces, absorption and scattering, affect the received loudness level. In this paper, the relation between the diffusion of a room and how it affects the binaural loudness perception is studied.

For studying this issue, some experiments were carried out, simulating different rooms and modifying the room acoustics parameters, absorption and scattering level, and extracting the binaural room response of every receiver and for every parameters combination. Then, the loudness level for each ear is analysed and the binaural summation is performed. The results show that the diffusion of a room affects the binaural loudness levels received, and also that the position of the listener in the room, closer or further from the walls, changes as well the binaural loudness perception of the receiver.

Keywords: loudness, binaural loudness, diffusion, room acoustics, scattering.
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1. Introduction

In psychoacoustics, one of the main goals is to translate a time waveform sound into a domain that can represent the response of human perception to that sound. Loudness is the psychological correlate of physical sound pressure level, it means, the perceived intensity of sound [1]. This transformation between the sound level in decibels and its perceived loudness is described in different loudness models [2, 3, 4]. From some of these models, ISO standards were set [5].

These models for predicting loudness from acoustical measurements of sound pressure often use a monophonic signal. The standardized loudness model ISO 532 [5] utilizes the sound signal recorded using a monophonic microphone in the absence of a listener [6]. Using an artificial head with microphones at both ears adds the effect of the torso and the head obstructing the measured sound [7]. The binaural nature of the auditory perception of human beings must be considered. The understanding of the binaural loudness perception is necessary for many applications. For instance, many projects work with audio immersion that uses binaural human perception for achieving virtual reality and full immersion [8].

Recently, there has been a growing awareness in psychoacoustics, and its relation with room acoustics is nearly investigated. The diffusity of a room can be affected by surface reflections [9] and the loudness perception was briefly commented in [10]. Inside a room, when a sound source emits a sound, this is spread until it reaches a wall, hitting them. In this boundary, two phenomena happen: the reflection of the sound and the absorption of it by the wall. The mechanism of the reflection is affected by two main features of the surface: the absorption coefficient and the scattering level. The directional loudness perception has been studied [11-15] but how the variation of these main acoustic characteristics of a material being a wall in a room affects the loudness level could help in the study of how to doing better design for rooms taking into account not just the distribution of the sound in the room but also how a listener would perceive the sound, more or less annoying, in a precise position with particular room acoustics parameters. Other studies assessed the loudness in directional sound fields [16].

The purpose of this paper is to investigate the relation between the binaural loudness level and the diffusion in rooms. This is done through experiments in which several room acoustic simulations in different scenarios with different room acoustics parameters, extracting a simulated sound in each listening position and, finally, getting the binaural loudness level, according to [17].

This paper is organised as follows. First, the binaural loudness implementation carried out in this study is reviewed and its stages are exposed. Then, the explanation of how the binaural room impulse response is simulated is briefly introduced. After that point, the experiments carried out are described along with the discussion of the results obtained. Finally, conclusions are presented.

2. Binaural model implementation

In this paragraph, the process for extracting the binaural loudness level from a stimulus is described. The loudness calculation stages for monaural extraction and the binaural summation are presented along with the binaural room impulse response extraction.

2.1. Loudness calculations

By definition, a loudness of 1 sone is produced by a 40-dB SPL, 1-kHz tone, and doubling or halving loudness in sones corresponds to a 10-dB increment or decrement in sound-pressure level, respectively. When approaching a diotic situation, however, the signals at the two ears tend to be weighted equally in contributing to overall loudness. The main stages for the calculation of the monaural total loudness can be seen in Figure 1.

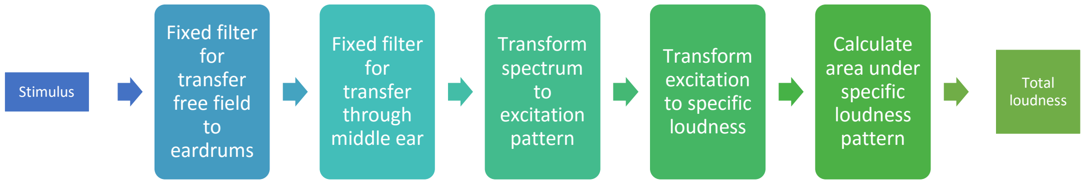

Figure 1 – Main (monaural) stages of models used for loudness calculations [17]

There exist several binaural loudness models [7, 17, 18]. All of them follow a rule of a summation of both contributions (right and left ears) in different proportions. In this paper, the perfect summation rule from [17] has been implemented for the binaural loudness calculations. In Moore's model, two independent calculations of both right and left ears are performed. Then, each result is perfectly summed to the other in order to follow the perfect summation rule [17].

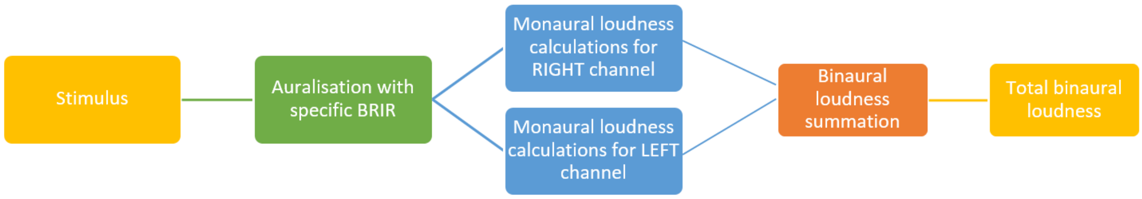

Figure 2 – Stages for binaural loudness calculations

For the calculation of the loudness level, the model of Moore and Glasberg [17] has been followed. In this model, the auditory frequency scale used is the equivalent rectangular bandwidth (ERB) and the equation for the specific loudness in a filter band is:

$$N' = C \cdot \left[\left(E_{sig} + A\right)^{\alpha} - A^{\alpha}\right] \tag{1}$$

where E_{sig} is the excitation pattern of the stimulus, A is a constant that is equal to E_{THQ}, that it is the excitation pattern at the hearing threshold, and C and α are constants empirically adjusted.

An auditory model is used for calculating an excitation pattern at auditory threshold. A gammatone filterbank with 128 filters is assumed. The calculation of the excitation pattern at the auditory threshold is done by generating pure tones at a filter with all the centre frequencies with an intensity that equals the minimum audible field at these frequencies. When all the tones are done, these are combined in one excitation pattern (Figure 3a).

a) *b)*

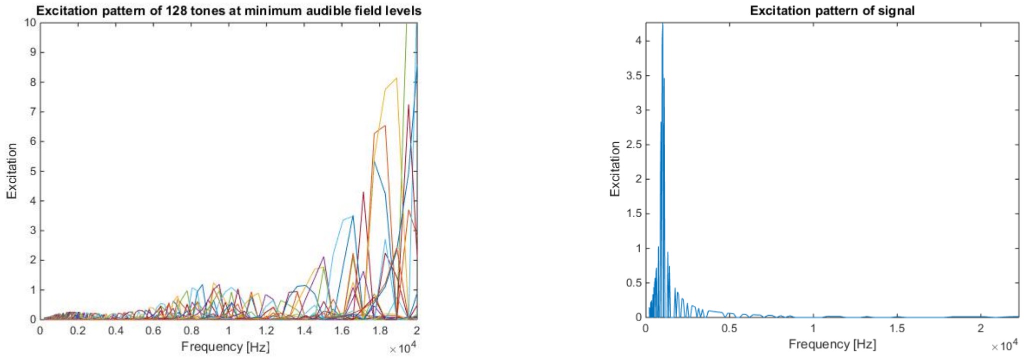

Figure 3 –

a) Excitation pattern of 128 tones at minimum audible field levels.

b) Excitation pattern of the stimulus (1 kHz pure sine tone).

Next, the calculation of the specific loudness of the stimulus is performed. For this task, using the auditory model, the excitation pattern of the signal must be calculated (Figure 3b), and then, applying Equation (1), the specific loudness of each ERB is extracted. Finally, to find the total loudness from specific loudness, scaling is applied based on the bandwidth of the ERB filters before summing. After that, the final loudness level is given in sones.

In the case of calculating binaural loudness, the basic mode of operation of the model is to calculate loudness for each ear separately. For binaural presentation, the overall loudness is obtained by simple summation of the loudness at the two ears. For diotic presentation, it means the same sound at each ear, the overall loudness is simply double that for each ear separately, according to Moore and Glasberg model, 1997 [17].

For getting the sounds that would reach each ear in a precise place of the room with a precise source, an extraction of the binaural room impulse response of every listener in all the different room conditions is simulated for doing a convolution with an anechoic sound. A binaural room impulse response is the impulse response that a listener would receive in each ear, with a precise source emitting and with the orientation of where the listener is pointing to. This is simulated used a head related transfer function applied to the room impulse response achieved in the receiver position. In this work, to investigate the influence of room acoustics on loudness perception, the binaural room impulse responses of all the combinations of scattering and absorption coefficients in all the listening points and for each source are calculated. By using these BRIRs, the effects of the reverberation of each measuring point can be added to an anechoic sound to analyse its loudness level.

3. Experiments

In this section, the different experiments to check the effects of room diffusity in binaural loudness perception are presented. The experiments include the simulation of two rooms with diverse geometries, a cubic and a rectangular parallelepiped room, and several configuration of the room acoustic parameters for, lately, analyse the binaural loudness level in different receiving points of them in all different cases.

Firstly, a definition of the geometry of the rooms used for simulating the different cases is presented. For doing this, the two rooms were built in Sketch Up [19] and, using a specific plugin, they were set up for its use in Odeon [20]. Through this acoustics software, all the sources and receivers were created with their specific orientation in elevation and azimuth, along with the definition of the different room acoustics parameters modified in the experiments (the absorption and the scattering). Finally, in

Odeon, the binaural room impulse responses for each point were calculated and extracted for their following processing in Matlab [21].

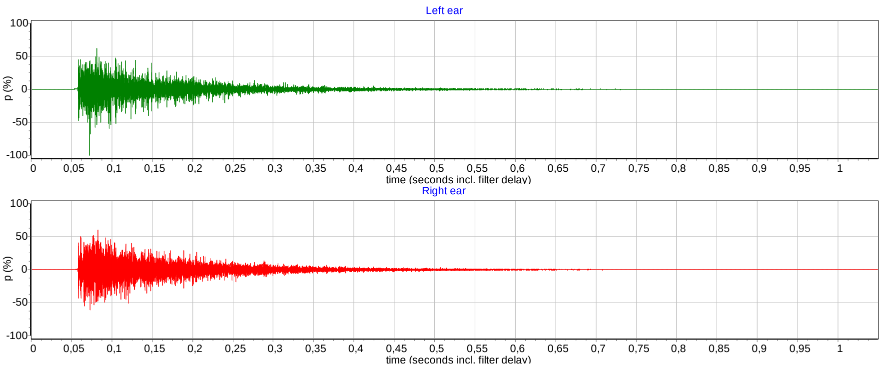

Figure 4 – Odeon BRIR results

An important stage of the loudness calculation is the calibration stage. In Matlab, sound read from wav files are normalized to have amplitude levels lying between 1 and -1. However, this will never reflect the true recording or playback levels of the sound. The amplitude of a sound can be scaled to have a desired level of decibels of sound pressure level. The reference level chosen for this calibration was the auditory threshold in the air, in Pascals, 20 μPa. A certain SPL in dB have to be chosen. In this paper, a 1 kilohertz sine signal with a sound pressure level of 40 dB was used. This signal was used as a stimulus in all different cases due to its equivalent loudness level: 1 sone (Figure 5).

A Matlab implementation for the loudness extraction was proposed in [22]. The auditory model is created using the HUTear Toolbox [23], for calculating the excitation patterns at the hearing threshold and for the excitation pattern of the stimulus. In this case, as it was said before, a pure tone of 1 kHz and 40 dB was used. The number of filters used for both calculation was 128. The loudness calculation proposed was modified and the equation used was (1), from [17]. The results get using this equation and this model can be observed in Figure 5.

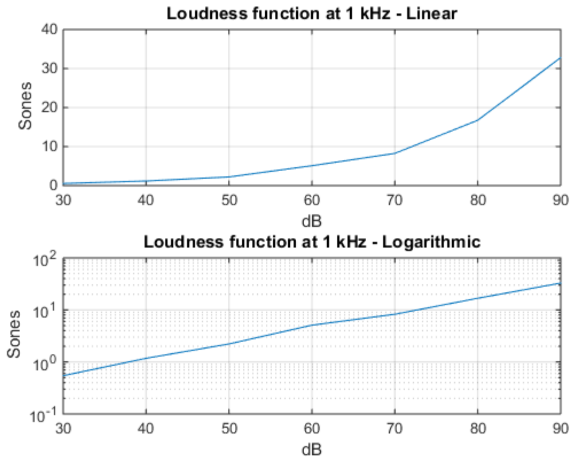

Figure 5 – Loudness function at 1 kHz in linear and logarithmic scales.

3.1. Scenarios

3.1.1. Rooms

Two different rooms have been simulated with different absorption and scattering conditions. There are some sources and several receivers in the different rooms. All the receivers are pointing to the emitting source. This is a relevant datum to notice, due to the binaural nature of the human listening experience. The head-related transfer function (HRTF) is the same for all the different cases but the binaural room response will change depending on where the listener is looking at.

The first room is a "shoebox" room of 10 meters' length, 7 meters' wide and 3 meters' height. This room has a sound source in the position (3.50; 1.50; 1.80) with an omnidirectional directivity pattern and three different sound receivers:

a) Receiver 1 (6.50; 9.50; 2.50): equally-distanced from all the surfaces, 0.50 meters, and close to a joint. In this position the effect of reflections from all the walls is expected to be noticed.
b) Receiver 2 (3.50; 5.00; 1.50): this position is the centre of the room. It is close to the source and it has also the effect of side and top and bottom surfaces.
c) Receiver 3 (1.00; 5.00; 1.25): close to one wall and in, approximately, the middle of the Z-axis. It has contributions mainly from the source, reflections from one wall on the right, the ceiling and the floor.

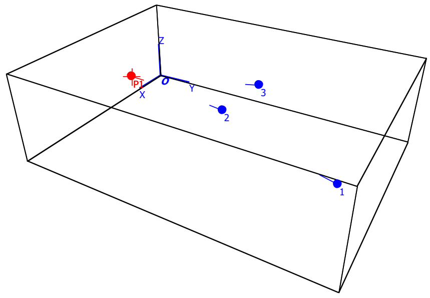

Figure 6 – Shoebox room (7x10x3)

The second room is a cube-shaped room. This room is equally sized in all the segments of the walls. It means, it is a cubic room. The side measures 5 meters. This cubic room has two sound sources, not emitting at the same time, but alternately, and both of them with an omnidirectional directivity pattern:

a) Source 1 (2.50; 2:50; 2.50): placed in the middle of the room.
b) Source 2 (4.00; 4.00; 4.00): placed near the walls in a corner of the room.

There are three receivers in the room. In both cases, with both sources, the receivers are in the same positions:

a) Receiver 1 (1:00; 1.00; 1.00): this receiver has contributions from all the walls because of its position in a corner, and from the sources directly.
b) Receiver 2 (0.50; 0.50; 0.50): this position is closer to the walls than receiver 1, therefore, the contributions due to reflections will be higher than in the previous measuring position.
c) Receiver 3 (3.00; 3.00; 3.00): it is almost in the middle of the room.

a) *b)*

Figure 7 – Cubic room (5x5x5)

a) With source 1 and receivers pointing to this source.
b) With source 2 and receivers pointing to this source.

3.1.2. Room acoustic parameters

The acoustic parameters to change in the walls were the absorption coefficient and the scattering coefficient of every surface. In all the cases, both, the absorption ant the scattering coefficients are the same for all the surfaces.

The values used for the absorption coefficients were: $\alpha = 0.1$ and $\alpha = 0.2$. Value for the scattering coefficients were from 0.1 to 1 in 0.1 steps. Moreover, value 0.01 was also chosen because of its proximity to 0 and for protecting the Odeon simulations from illogical calculations.

3.2. Results and discussion

3.2.1. Cubic room

In this geometry, the monaural studies give some results not suitable for getting valuable conclusions (Figure 8). For that reason, in the cubic room with the different scattering and absorption configurations, together with the different active sources used, the discussion will be carried out with only the binaural loudness results.

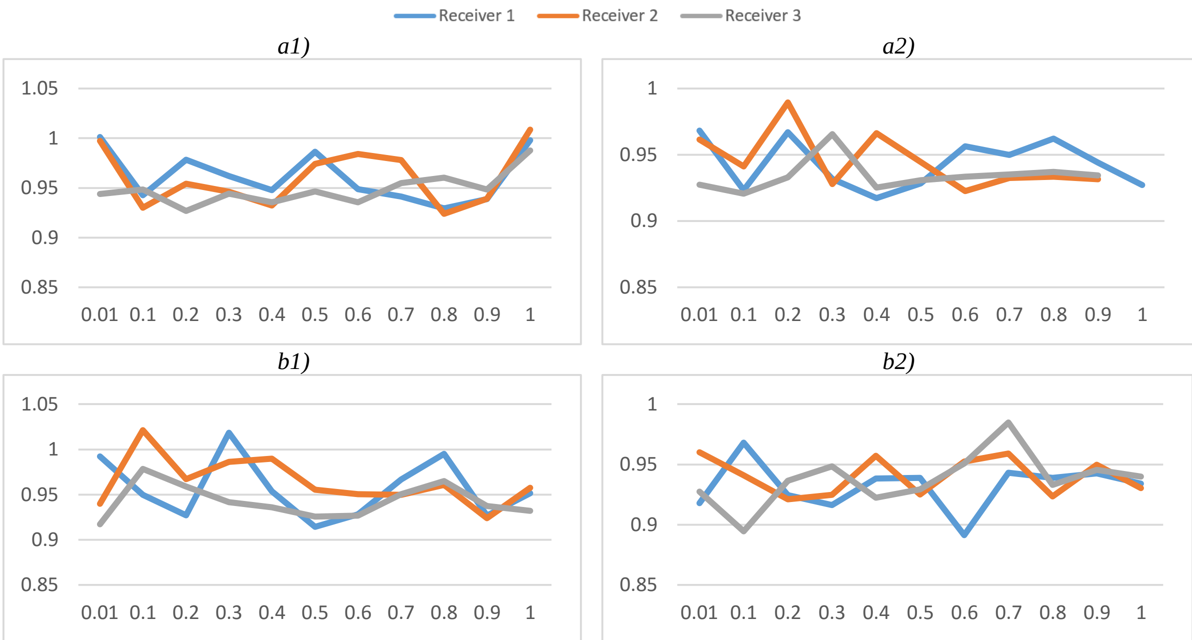

Figure 8 – Monaural loudness evolution Cubic room (Scattering level in X-axis, loudness level in Y-axis)
a.1) With active source 1 and α=0.1(upper left); a.2) With active source 1 and α=0.2 (upper right)
b.1) With active source 2 and α=0.1 (bottom left); b.2) With active source 2 and α=0.2 (bottom right)

In the binaural results (Figure 9), the evolution of the loudness level as the scattering increases is more noticeable. In the *a.1* of Figure 9 case, receiver 1 and 2 grow as the loudness increases, however, receiver 3 keeps almost constant for all the scattering values and in the different cases of active sources and absorption values. This is due to the distance from the walls and its position in the room. In this kind of room shapes, the sound-energy distribution in the middle of the room is nearly constant and consequently, the binaural loudness levels calculated in that point maintain the same behaviour too.

Nevertheless, for receivers 1 and 2 the effect of the contributions from the walls is quite noticeable in all the cases and with obvious differences within the absorption values. As the scattering level increases, the loudness level increases too for all the cases. With the lower absorption value, α=0.1, the loudness levels for receiver 1 and 2 and for both cases of the two active sources are quite close until 0.3 (0.4 in the α=0.1 because of the less absorption in the room and more diffuse field in the room), when the receiver 2 loudness levels start increasing higher than the receiver 1 loudness levels. This is due to the big proximity to the walls, and their contributions to the listener. For receiver 1 is the same behaviour but to a lesser extent because is further than receiver 2 from the walls. The behaviour of both receivers is almost the same with active source 2, and it shows that in rooms with this geometry, the positions of the source is not so relevant for the final binaural loudness levels.

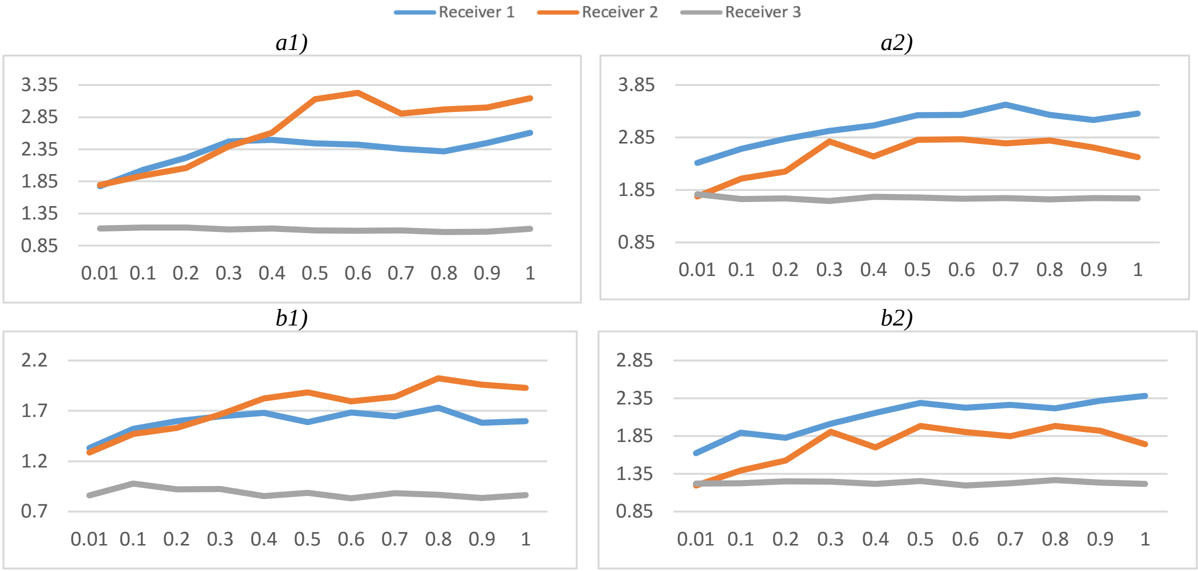

Figure 9 – Binaural loudness evolution Cubic room (Scattering level in X-axis, loudness level in Y-axis)
a.1) With active source 1 and α=0.1(upper left); a.2) With active source 1 and α=0.2 (upper right)
b.1) With active source 2 and α=0.1 (bottom left); b.2) With active source 2 and α=0.2 (bottom right)

However, the tendency changes in the cases *a.2* and *b.2* of Figure 9. In these cases, α=0.2. The increasing behaviour is preserved, but the higher values correspond to receiver 1. This is because the higher absorption level of α=0.2. Now the contributions from the walls are lower and the sound energy distribution close to the centre of the room gives higher contributions than the contributions from the walls, so now, the summation of sound-energy density of the diffuse field with the contributions from the walls are higher than only the contributions from the walls.

3.2.2. Shoebox room

Firstly, the analysis for this geometry with the lowest absorption value of the chosen for the calculations, α=0.1, was carried out. The evolution of the loudness level for this case can be seen in Figure 10. In the monaural analysis (Figure 10a), the tendency of the loudness in all the receivers is going from a higher value to a lower one.

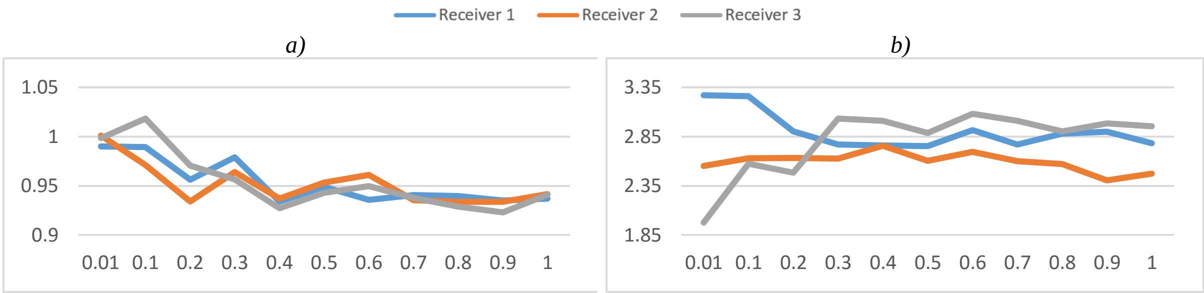

Figure 10 – Shoebox room loudness levels (Scattering level in X-axis, loudness level in Y-axis)
a) Monaural loudness evolution of the three receivers with α=0.1 (left).
b) Binaural loudness evolution of the three receivers with α=0.1 (right).

In the binaural results (Figure 10b), the tendency is a light decrease for receivers 1 and 2 and in receiver 3 there is a stronger increase in the lowest part of the scattering levels and a stabilisation from

0.3 to 1. In the case of scattering of 0.01 it is more obvious the effect of the listening position in the room for modifying the loudness level. Receiver 1 has the highest loudness level, receiver 2 is in the middle and receiver 3 the lowest. This is because receiver 1 is quite close to 3 surfaces (XZ, ZY and XY) at the corner, with just 0.5 meters from all of them, and it receives more concentrated contributions than the other receivers. Receiver 2 is in the middle of the room and the direct sound in addition to the contribution from the reflections of all the walls is balanced, giving it the most intermediate values of loudness of all receivers in the configuration studied. However, receiver 3 has the lowest value of binaural loudness perceived. A plausible explanation for this is that it only has main contributions from two of the walls, due to its closeness (YZ and XY) and the distance between it and the rest of the walls makes it having less sound contributions in each ear channel.

Finally, as the scattering level increases, and the diffusivity of the room rises, the loudness level change. For receiver 2, the loudness level is almost steady for all the scattering values because of its position. For receiver 3, the results increase as the scattering rises, until 0.3, and from that value the loudness level keeps steady. This is due to the raise of the diffusion of the room and for the more shared sound energy in all the room added to the contributions from the reflections of the surfaces close to the receiver. In receiver 1, loudness level decreases until 0.3 and then the values are intermediate between receiver 2 and 3 values in a constant way. The explanation is that the contributions from the closer walls rises the loudness perception but, with the further distance from the source, the direct contributions are not so high than in the other cases, so for that, the binaural loudness level is like that. If the source would be closer to this receiver, the loudness levels would be the highest of all the receivers (direct sound + reflections).

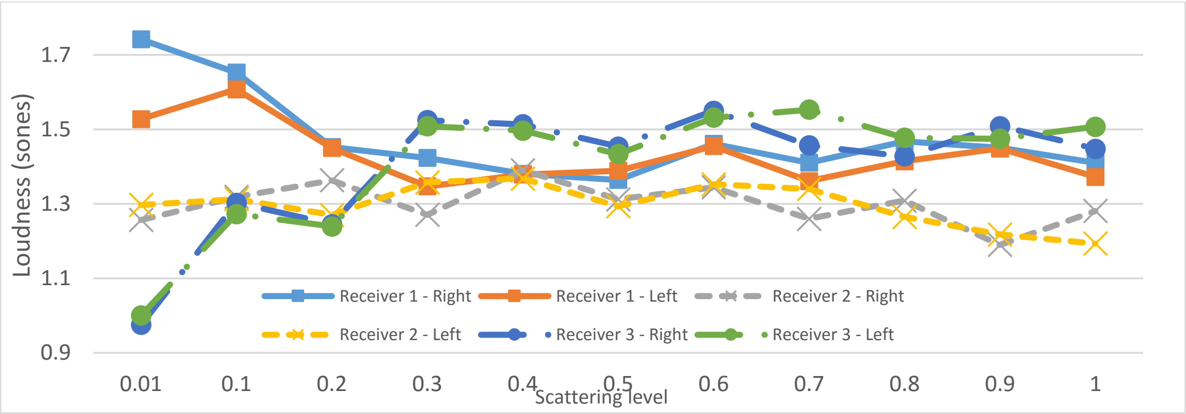

Figure 11 – Right and left loudness values for shoebox room with α=0.1

In the case of α=0.2, Figure 12, the evolution of the monaural loudness shows a tendency in the approximately of the values with higher scattering levels. But in intermediate values (0.2-0.5) the difference between the receivers is bigger. Receiver 2 values stabilised before the other receivers due to its position in the middle of the room. Receiver 1 has a higher level due to the contributions from the near reflections of the walls next to it. However, receiver 3 has the lowest value of all the three because of the weak contributions from the closest walls to it and the source. At lower scattering levels, receiver 1 and 2 have the same scheme in the evolution of the loudness, having high values when the scattering is nearly absent and start descending and stabilising as the scattering increases. Receiver 3 has a lower initial value and the loudness level decreases as the scattering increases until a high diffuse sound field exists, from scattering 0.6.

In the binaural analysis, receiver 1 has the highest initial loudness values, due again to the proximity to the walls, and as the scattering increases the loudness decreases. Receiver 2 keeps a more stable value of loudness for all the scattering levels but with a soft decrease as the sound energy is more diffused. However, receiver 3 has a different evolution than the others. It starts with the lowest loudness level of all, because the reflections are really weak in that position, and as the scattering increases and when the condition of a diffuse sound field is being reached, the loudness levels increases (from 0.01 to 0.3). From 0.3, the levels start a light decrease keeping an approximately steady value of loudness for the rest of the scattering levels.

In this case of α=0.2, the results are similar in the evolution of the binaural loudness levels of all the positions than with α=0.1 case, but with the difference that the loudness levels are lower due to the increase in the absorption coefficient, reducing the density of the sound energy inside the room.

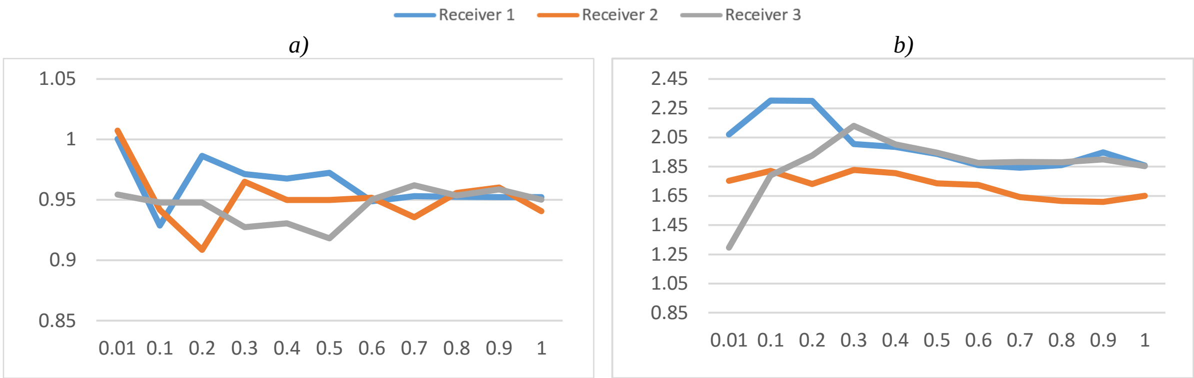

Figure 12 – Shoebox with α=0.2 (Scattering level in X-axis, loudness level in Y-axis)
a) Monaural loudness evolution of the three receivers with α=0.2 (left).
b) Binaural loudness evolution of the three receivers with α=0.2 (right).

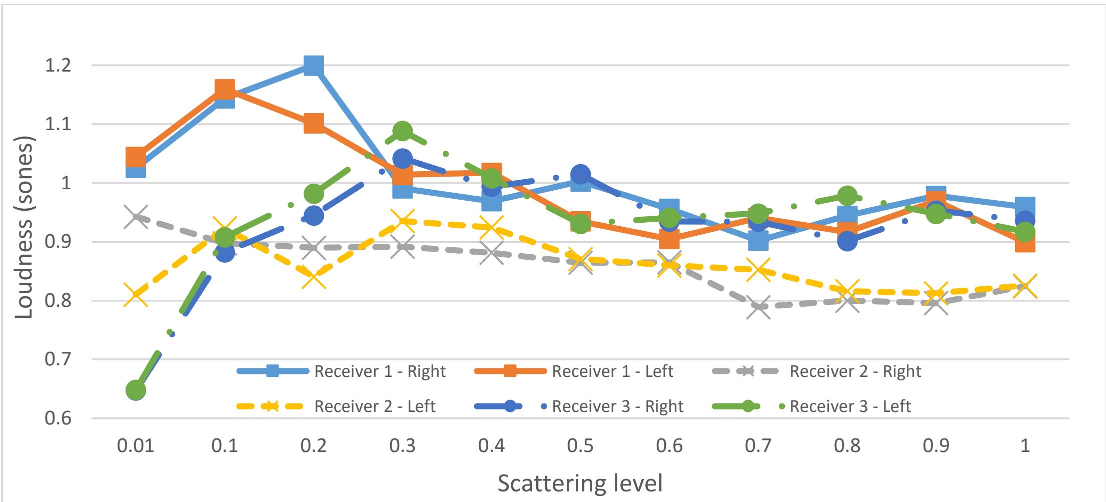

Figure 13 – Right and left loudness values for shoebox room with α=0.2.

4. Conclusions

In this paper, a revision of the binaural loudness within the diffusity of a room, and how its physics may affect the auditory annoyance sensation is reviewed. Then, the binaural loudness model implementation used for the calculations of this study was assessed. The next section was used for presenting the experiments carried out and their results. In one subsection, how the calculations of the binaural loudness were performed were shown, and next, the different scenarios simulated and the modified parameters were explained. In the following subsection, the presentations of the results and a discussion about them is carried out.

Results show that the binaural loudness levels are dependent of the geometry of the room and also of the position of the listener in them, together with the variation in the room acoustics parameters of the walls. The proximity of the listener to the walls increases the loudness levels, in a stronger way when the absorption values are lower. In the cubic room, where the diffuse field is more pronounced, the loudness level considerably increases. In the shoebox-shaped room, the growth of the scattering levels makes the loudness levels stop growing in a certain point and then they stabilise, giving a quite similar loudness level in all the positions when the scattering reaches the highest value. This is independent of the position of the listener.

However, a common result in the analysed rooms showed that when the receiver positions is in the middle of the room, nearly equidistant from all the walls, the loudness levels in that position are almost always the lowest in all the cases than in the other listening positions, in a greater or lesser extent. In addition, the analysis shows that the binaural loudness levels are almost independent of the position of the source in the room. Further experiments should be carried out in more complex room geometries and with different sound sources to study the behaviour of the binaural loudness.

Acknowledgments

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