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Analysis of the room acoustic texture parameters in function of diffusers location and distribution inside a small concert hall

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ABSTRACT

To study the room acoustic texture, defined through a group of parameters derived from the cumulative energy of the early reflections temporal information, different room configurations inside a small concert hall with fixed room volume were analyzed. The proposed texture parameters are the expected texture (ETx), the mixing time (Mt) and the distance between models (DBM) of the monaural impulse responses. The cases consisted in: a) six configurations with constant diffusers surface extension positioned at different locations on the lateral walls, b) three configurations with ceiling, lateral, rear and front walls set at the same acoustic condition, i.e. reflective, absorptive and diffusive, and c) constant surface extension of just one wall with different coatings. For this, a series of monaural impulse responses (RIRs) recorded at ESPRO (IRCAM) were processed. For case a) texture parameters remained almost constant through all variations; b) Although ETx showed higher values in the diffusive condition compared to the reflective condition, Absolute DBM showed lower values for the reflective and absorptive conditions. For case c) spatial average ETx showed no significant improvement of adding one diffusive wall from the fully reflective one.

Keywords: Room acoustic texture, diffusion, impulse response.

1. INTRODUCTION

Room acoustic texture is defined by Beranek (1, 2, 3) as the subjective impression listeners derive from the temporal and amplitude patterns of early reflections, at the receiver's locations inside the room. Traditionally, it was assessed by visual inspection of the room impulse responses (RIRs) or counting reflection's peaks (4, 5). Taking into account that the distribution of reflections in the later part of the reverberation tail is of Gaussian type and totally mixed, the early part of every RIR contains the most important temporal information. Therefore, objective measures should be provided in order to get useful information on the acoustic quality of the early and late reflections. Furthermore, their correlation to the subjective perception should be investigated.

In this paper, the case of a rectangular concert hall has been considered by varying the acoustic conditions of the ceiling, front, rear and lateral walls. Texture parameters have been assessed on previously measured impulse responses in Shtrepi et al., 2018 (8), and compared to the ISO 3382 objective parameters.

1.1 Definitions and previous research

To define a group of parameters describing the texture of a RIR, a few assumptions have been made (6): the early reflections have been defined as every amplitude outlier present in a room impulse response (7, 8), and the mixing time (Mt) as the instant when their cumulative energy reaches 99% of the total energy. For this calculation, a moving median filter is applied to the energy time curve on a temporal window with length dependent on the lowest analysis frequency band, thus obtaining a RIR only composed of median values; finally the outliers temporal information is computed by subtracting this from the full RIR. With the outliers identified, the echo density function (*edf*) corresponding to the RIR under analysis, is defined as their cumulative energy over time. From this processing, a group of descriptors are defined comparing this "actual" *edf* with two models, named *ideal* and *expected*,

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that jointly describe the room acoustic texture, at one point in the sound field. These models are "capacitor charge functions" curves over time, as shown in (9). Both curves are defined by the information at two instants: the "ideal" curve is defined by the Mixing time (Mt) and the initial time delay gap (ITDG) the actual RIR has. The "expected" curve is defined by the best fit to the *edf* of the actual RIR. Comparing the actual *edf* with both model curves, a set of parameters are defined. From those, the main texture parameters are the expected texture (ETx, {0, 1}), the mixing time (Mt, [ms]) and the distance between models (DBM, {-∞, +∞}) (6). In order to assure a good acoustic texture, that means a low "acoustic distortion" (e.g. acoustic center shifting, frequency coloration, acoustic width modification), these texture parameters should report short Mt, and a very small value of DBM (very close to zero), exhibiting an ETx with a value between 0.8 and 1 (6). Through a dedicated software designed to calculate these parameters over a set of RIR data, results can be shown over third octave frequency bands, allowing the user to know the single frequencies that need treatment, and full frequency range results (32 Hz to 16 KHz), i.e. global results. To obtain a global DBM value excluding the sign, which means displacement direction of the expected *edf* curve with respect to the ideal curve, the average absolute DBM values (Abs DBM) were calculated.

Although the RT [s], EDT [s], room volume [m^3] and diffusion of the sound field influence with different sign and weights those parameters related to the acoustic texture, preliminary studies (12) showed a reduction of Mt while increasing sound field diffuseness, for constant RT, EDT and room volume. On the other hand, ETx showed an increase and Abs DBM a decrease, for an increase in the diffusion of the sound field, keeping the RT, EDT and room volume constant. Also, a reduction of ETx and a reduction of Mt were observed for a reduction of RT, and an increase of Abs DBM was observed for a reduction of EDT, for constant diffusion surface and room volume. As it can be observed, this analysis allows us to know the balance between the traditional acoustic variables, in relation to the behavior of a RIR without early reflections - no reflection´s amplitude outliers - , that is without "acoustic distortion".

Considering that an increase of the acoustic diffusers surface extension (adding acoustic diffusers in a room) would lead to an increase of the degree of diffusion of the sound field (6, 13), a Multi Layer Perceptron Neural Net model (MLP NN) was developed with diffusers surface extension (*Diff surface*) [m^2] as a dependent variable. For the smallest rms error result model, the independent variables showed to be Abs DBM and EDT, and their importance over *Diff surface* were 41.7% and 58.3%, respectively.

Afterwards, a mathematical relation between *Diff surface* and both variables could be stablished, independently. With this information, an equation for the sound field diffuseness (SFD) was developed as shown in eq 1, eq 2, eq 3 and eq 4, resulting in a parameter that varies between 0 (minimum) and 1 (maximum).

$$Diff\ surface \propto \frac{1}{Abs\ DBM}, \qquad (1)$$

$$Diff\ surface \propto EDT^3, \qquad (2)$$

As MLP NN models are based in summation, a weighted approximation for sound field diffuseness could be made trough (3):

$$d \propto \frac{0.417}{Abs\ DBM} + 0.583 \cdot EDT^3, \qquad (3)$$

Where:

d: is the sound field diffuseness,

Abs DBM: is the absolute DBM value,

EDT: is the early decay time.

As larger diffusers surface extension produces larger sound field diffuseness, d is bounded between 0 and infinite. For this reason, the final equation for sound field diffuseness bounded between 0 and 1, SFD, is:

$$SFD = \frac{d}{1+d} \qquad (4)$$

At this point, a clarification should be made: our proposal considers the sound field diffuseness is not a state but a process; a process that takes the room from its deterministic state to it´s stochastic one. The duration of this process is the mixing time (Mt). That's why SFD is maximum when this process is identical to the ideal one, regardless of its duration.

2. METHODS

In this work, a case study has been considered, that is, the test room ESPRO (Espace de Projection, at the Institut de Recherche et Coordination Acoustique / Musique), which is part of the laboratories of IRCAM in Paris. It is a small size concert hall, with a volume of 3720 m^3, a capacity of 350 seats and a height of 10m. It has been studied in previous works (9, 10, 11). It has a variable passive acoustics with known surface properties: the characteristics of the walls and the ceiling can be modified by 516 rotating triangular prisms, exposing the interior of the room to 4 different types of coating topologies: absorbing, reflective, diffusive 1 (s = 0.75) and diffusive 2 (s = 0.25). Sets of 3 prisms (arranged horizontally or vertically) are configured in functional units of 2.33 m by 2.33 m (12). The room has 4 rows of these units, and 9 columns in its largest dimension and 6 columns in the smallest, as can be seen in Figure 1. All configurations had a reflective floor.

The configurations of the room have been characterized acoustically through measurements based on ISO 3382, (9). To this aim a set-up of 24 omnidirectional microphones (Sennheiser KE-4, 8 mm), one artificial head (ITA recording head) and two sound sources (ITA Dodecahedron Loudspeaker) have been used as shown in Figure 1 - right. Further details of the measurement chain can be found in Shtrepi et al. 2016. Afterwards, texture parameters were processed through a specially developed software at UNTREF University.

2.1 Configurations

Three groups of configurations of the concert hall have been used in this work. They were obtained by rotating the prism panels into the reflective, absorptive and diffusive 1 conditions. It should be noted that all configurations presented a reflective floor and the 1^{st} level of panels has been fixed to absorptive and remained in that condition even when the rotating panels were set to reflective or absorptive mode, for each condition.

Case A includes six configurations of the room that have been presented in Shtrepi et al. 2018 (10). The location of diffusers with a constant surface extension has been varied on the long lateral walls at three different positions: front, middle and back. The remaining rotating panels have been set first in the reflective and then in the absorptive condition, and the 1^{st} level of panels has been fixed to absorptive and remained in that condition even when the rotating panels were set to reflective or absorptive mode, for each configuration. The aim of this group analyses is to study the differences in texture parameters as a function of the location of a constant diffusers surface extension on the lateral walls of the concert hall.

Case B includes three configurations of the concert hall where the variable panels on the ceiling, lateral, front and rear walls have been set entirely in a reflective, absorptive and diffusive 1 condition. The aim of this group analyses is to study the acoustic texture within three different extreme acoustic configurations maintaining a constant volume.

Case C considers two configurations of the hall where only one long lateral wall has been set in two different acoustic conditions, that is, reflective and diffusive - see Shtrepi et al, 2016 (9) -, as can be seen in Figure 2. The aim of this group is to investigate the effects of a single surface on the texture parameters near and far from the test wall. In these conditions the focus was put at the four near microphone positions at a distance of 2.15 m from the test wall, and the four far microphone positions were positioned at at 8.96 m from it. The ceiling and the other walls were fixed to be absorptive.

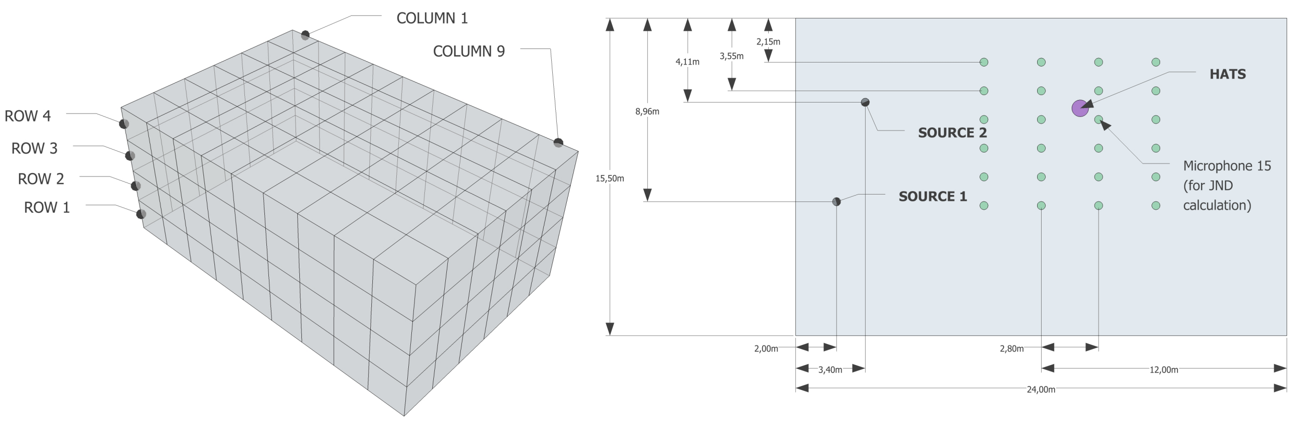

Figure 1- Left. Volumetric scheme of ESPRO IRCAM small concert hall. Functional units (2.33 m x 2.33 m), each composed by 3 (triangular) prism units, are distributed in rows and columns on each surface of the hall (except floor). Right. Floor plan of the test room with sound sources, measurement microphones (green circles) and head (Artificial Head) positions.

3. RESULTS

3.1 Experiments CASE A

As highlighted above, the aim of this group analyses is to study the differences in texture parameters as a function of the location of a constant diffusers surface extension on the lateral walls of the concert hall. In Table 1 are shown the global ETx, Abs DBM, Mt and Early Decay Time (EDT) results for each configuration, as average results from 500 Hz to 1 kHz third octave frequency bands.

Table 1. Configurations and their respective texture average results and standard deviations (S. Dev.), for 500 Hz, 630 Hz, 800 Hz and 1 kHz frequency bands.

Predominant surface acoustic condition	Sound Source	Location of the Diffusers surface extension	ETx [-]		Abs DBM [-]		Mt [ms]		EDT [s]	
			Value	S. Dev.	Value	S. Dev.	Value	S. Dev.	Value	S. Dev.
Reflective	S1	Front	0.68	0.18	1.89	1.59	355.7	39.6	2.62	0.2
		Middle	0.687	0.18	2.14	1.8	345.1	47.6	2.57	0.24
		Back	0.683	0.17	2.1	1.59	356.1	48.9	2.62	0.24
	S2	Front	0.688	0.18	2.2	1.62	364.4	49.8	2.68	0.28
		Middle	0.666	0.2	2.09	1.99	367.3	49.8	2.69	0.23
		Back	0.684	0.18	2.11	1.69	361.8	46.1	2.69	0.27
Absorptive	S1	Front	0.585	0.21	2.52	1.78	160.8	24.1	1.04	0.15
		Middle	0.617	0.2	2.34	1.79	160.9	21.4	1.05	0.12
		Back	0.639	0.19	2.32	1.82	157.3	23.6	1.02	0.15
	S2	Front	0.619	0.21	2.55	2.11	168.4	28.7	1.09	0.15
		Middle	0.638	0.19	2.41	1.97	166.5	27.1	1.08	0.14
		Back	0.636	0.19	2.37	2.01	159.8	25.9	1.04	0.15

The full band standard deviations of ETx, Mt and DBM were studied at positions near the artificial head location. These deviations could be a first approximation to their possible JNDs based on a previous subjective study on the same configurations in Shtrepi et al. 2018 (10). This study showed that listeners (24 subjects) were not able to distinguish perceptually between the different locations of the diffusive surface at a statistically significant level. This was not possible also when the most asymmetric conditions were compared, i.e. the front and back locations of the diffusive surfaces.

Based on this perceptual result, it could be discussed that the variations of the texture parameters corresponding to the omnidirectional microphones close to the head and torso simulators, could be considered an approximation to their respective JNDs.

RIRs from the monaural microphone closest to the artificial head position (microphone 15) as shown in figure 1, was selected for ETx and DBM analysis, for the three conditions and two sound sources. From their global standard deviation and average results, a possible JND was inferred.

Considering that in the subjective tests between the three conditions (10) there was no clear differentiation between these, the global JND's for ETx and DBM parameters were calculated as the largest quotient between the standard deviation and the mean value over frequency bands, for both sound source positions, in the microphone positions closest to the head and torso simulator. For Abs DBM, its calculated global – full band - JND was 26%, and for ETx, its calculated global – full band - JND was 9.2%.

3.2 Experiments CASE B

The results of the Case B configurations aimed to show the acoustic texture data in three extreme acoustic conditions of the variable panels, i.e. reflective, absorptive, and diffusive, maintaining a constant volume of the hall. ETx, DBM, Mt and EDT average results for the reflective, diffusive and absorptive conditions, for 500 Hz to 1 kHz third octave frequency bands, are shown in Table 2.

Table 2. ETx, Abs DBM, Mt and EDT average results and standard deviation (S. Dev.) for the three extreme acoustical conditions: reflective, diffusive and absorptive, for 500 Hz, 630 Hz, 800 Hz and 1 kHz frequency bands.

Predominant acoustic condition	Sound source	ETx [-]		Abs DBM [-]		Mt [ms]		EDT [s]	
		Value	S.Dev.	Value	S.Dev.	Value	S.Dev.	Value	S.Dev.
Reflective	S1	0.68	0.16	2	1.65	361	46.3	2.64	0.23
	S2	0.7	0.16	2	1.49	369	50.3	2.71	0.26
Diffusive	S1	0.68	0.18	2.6	2	289	34.2	2.14	0.17
	S2	0.69	0.17	3	2.39	294	39.7	2.14	0.16
Absorptive	S1	0.63	0.2	2.4	1.91	147	24.5	0.96	0.14
	S2	0.62	0.21	2.4	1.92	156.9	27.2	1.07	0.14

Taking into account that EDT values are shorter for the diffusive condition than the reflective one, average Abs DBM results for 500 Hz to 1 kHz frequency bands, showed better values for the reflective condition than the diffusive condition (2 vs. 2.6, 2 vs. 3), with differences larger than the previously inferred JND, probably because of the larger RT; average ETx results for the reflective and diffusive predominant conditions showed to be into the corresponding JND variation, while ETx for the absorptive condition showed a reduction larger than the previously calculated JND. Mt Results showed to be better (smaller) for the diffusive condition than for the reflective one.

Considering the applied excitation signal (40 Hz to 10 kHz), full bandwidth Abs DBM, ETx and SFD graphs show a more complete description of the early sound field.

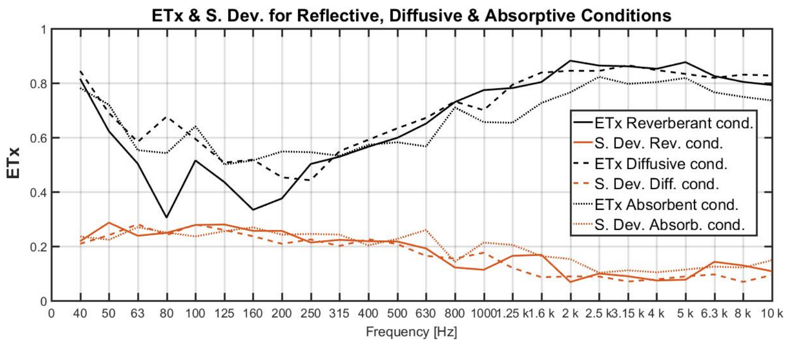

Figure 3 - Expected texture (ETx) and standard deviation (S. Dev.), over third octave frequency bands for the Reflective, Diffusive and Absorptive conditions.

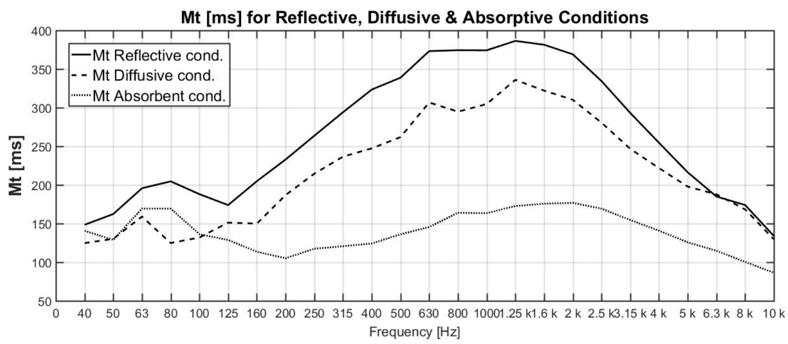

Figure 4 - Mixing time (Mt) over third octave frequency bands for the Reflective, Diffusive and Absorptive conditions.

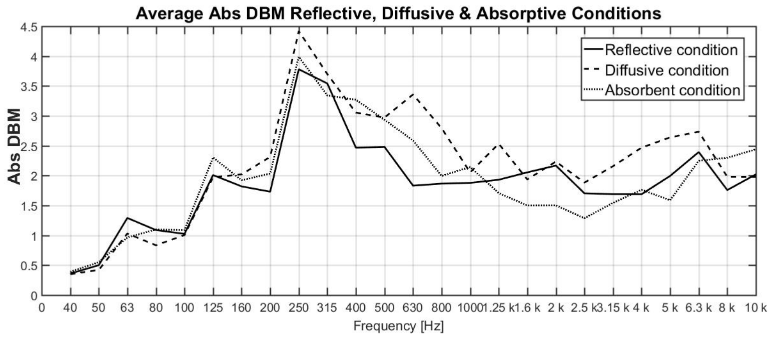

Figure 5 - Absolute Distance Between Models (Abs DBM) over third octave frequency bands for the Reflective, Diffusive and Absorptive conditions, for sound sources 1 and 2.

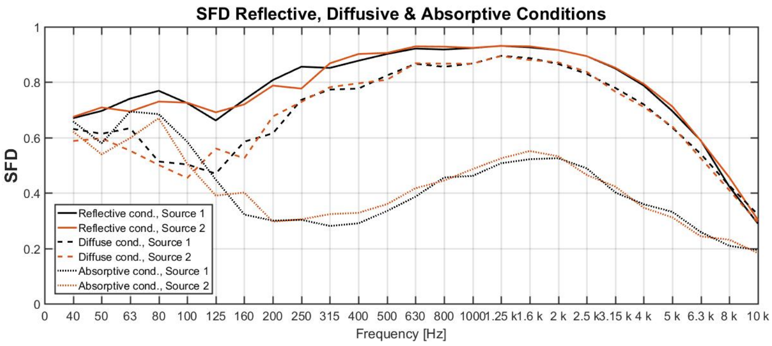

Figure 6 - Sound field diffusiveness (SFD) over third octave frequency bands for the Reflective, Diffusive and Absorptive conditions, for sound sources 1 and 2.

Figure 3 shows the expected texture (ETx) for the three conditions. It can be seen there is no considerably difference between them while their global values differences do not vary more than a JND. Figure 4 shows the mixing times (Mt) for the three conditions. The absorbent condition presents a much shorter Mt than the other conditions (approximately 50 % less). Abs DBM Over third octave frequency bands in Figure 5 shows a lack in diffusers efficiency at the same frequency band, 200 Hz to 800 Hz (approximately), for the three conditions. Although differences on Abs DBM between the three conditions are small, the EDT values of the absorptive condition produce a better diffusion process - higher SFD values - than the others, as can be seen in Figure 6. Also, it can be seen the effect of the diffusers in the low frequency – 40 Hz to 250 Hz approximately - due to their size.

The largest the temporal diffusion process duration, the more difficult to fix the initial time delay gap (ITDG) to Mt interval uniformly in time with small amplitude reflections. For this case, the reflective condition shows an average (full band) duration of 263 ms, the diffusive condition shows an average (full band) duration of 217 ms, and the absorptive condition, 139 ms.

3.3 Experiments Case C

The aim of these group analyses is to study the effect of a constant surface extension of just one wall in two different conditions, that is reflective and diffusive, on the texture parameters at receiver positions near and far from the test wall. The variations [%] between the four near microphone positioned at a distance of 2.15 m from the test wall, and the four far microphone positioned at 8.96 m from it, have been assessed.

The results reported in Tables 3 and 4, show that in none of the cases the sound field is uniform, which is expected from the asymmetric acoustic conditions presented in Case C. It can be noticed that parameters vary with distance to the test wall, which is coherent also with the subjective results shown in Shtrepi et al., 2016 (9).

Sound field diffuseness, observed through Abs DBM, (also) depends on the location of the sound source, i.e. significant differences between the two source positions could be observed.

ETx and Abs DBM *Variations between Near and Far* [%] positions show an improvement - the smaller the variation, the better - (for both sound sources) in the diffuse wall compared with the reflective one, for 500 Hz to 1 kHz bandwidth; a broader bandwidth can also be seen in figure 7.

Spatial, near and far average results of ETx, Abs DBM, Mt and EDT, from diffuse wall condition show no substantial improvement compared with the reflective one, this means variations are less than calculated global JND*s* from Case A.

Temporal sound field diffuseness (SFD) over third octave frequency bands, as described in eq. 4, for both conditions, close and far from the test wall, are shown in Figure 7.

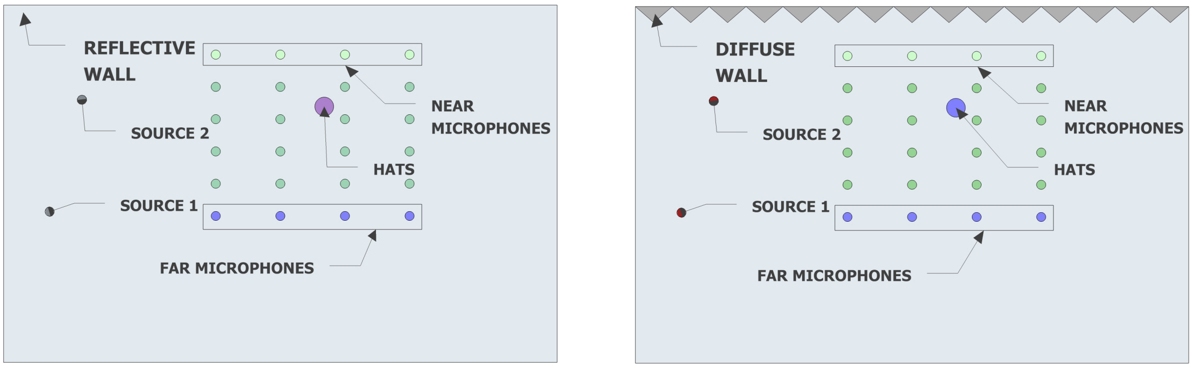

Figure 2. Scheme of ESPRO's (IRCAM) coated wall with case C conditions: reflective (left) and diffusive (right). Boxed: 4 microphone positions near and far away the reflective and diffuse wall.

Table 3. Reflective wall average global results for 500 Hz to 1 kHz third octave frequency bands. Results for two sound sources and three positions: Near the reflective wall, average for all microphone positions and far from the reflective wall.

	Position (ref.-coated wall)	**ETx [-]**	**Abs DBM [-]**	**Mt [ms]**	**EDT [s]**
Source 1	Near	0.712	2.27	165.4	1.02
	Average	0.65	2.4	161.7	1.05
	Far	0.599	3.44	158.1	1.07
Variation between Near and Far [%]		18.8	34	4.6	4.9
Source 2	Near	0.566	2.79	161.6	1.13
	Average	0.642	2.25	166.2	1.10
	Far	0.672	2.27	173.3	1.11
Variation between Near and Far [%]		18.7	22.9	7.2	1.7

Table 4. Diffusive wall average global results for 500 Hz to 1 kHz bandwidth. Results for two sound sources and three positions: Near the reflective wall, average for all microphone positions and far from the reflective wall.

	Position (ref.-coated wall)	**ETx [-]**	**Abs DBM [-]**	**Mt [ms]**	**EDT [s]**
Source 1	Near	0.645	2.84	183.9	1.24
	Average	0.628	2.35	172.1	1.19
	Far	0.709	2.43	166.7	1.19
Variation between Near and Far [%]		9	16.8	10.3	4.2
Source 2	Near	0.55	2.55	175.9	1,27
	Average	0.567	2.71	179.3	1.27
	Far	0.631	3.4	186.5	1.29
Variation between Near and Far [%]		12.8	25	5.6	1.5

From Figure 7, a slight improvement in the sound field diffuseness is observed for diffuse wall condition, close and far from the wall (8 % global improvement with reference to the reflective wall). As found in (9), among several objective coincidences, EDT gets longer for diffusive wall. For comparison, the SFD of all absorbent condition was added to figure 7. It also can be observed the macroscopic shape of the curves seems to be established by the preponderant (absorbent) room acoustic condition.

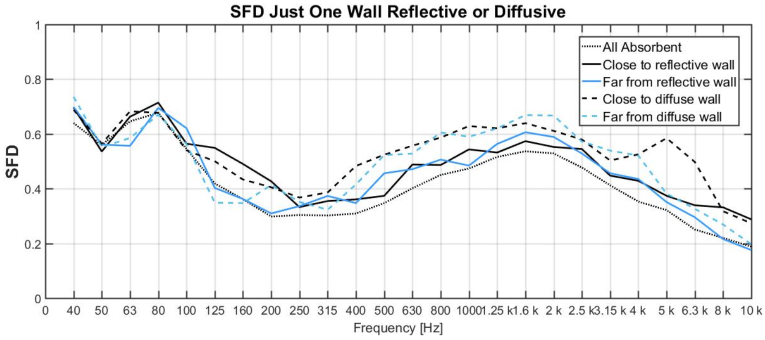

Figure 7 – Sound field diffusiveness over third octave frequency bands, for jus one wall reflective or diffusive, close and far from the test wall. SFD Of "all absorbent" condition was added for comparison.

4. DISCUSSION AND CONCLUSIONS

At this instance one may say that *temporal diffusion* is the phenomenon that leads the room from the ITDG until it reaches Mt, while the way in which this phenomenon develops - in time – may be called *acoustic texture*. Acoustic design could begin by stablishing RT with a given room volume, this would lead to a certain Mt. Afterwards, a target SFD can be achieved by adding diffusers, always maintaining a constant RT, but consequently reducing Mt. The proposed acoustic texture parameters quantify the room´s behavior in the early part of their room impulse response development. Results show that large EDT values with small Abs DBM present high temporal diffusion process (SFD) values. In this large scale and controlled situation, proposed texture parameters showed comparable behavior to those obtained in preliminary studies (12); acoustic texture, sound field diffuseness and mixing times are EDT, RT, room volume, diffusers extension [m^2], diffusers efficiency, sound source and receiver locations, dependent. From case a) a first approximation to JNDs for ETx and DBM could be derived. The evidence through the texture parameters would show that the (direct) relationship between the scattering coefficient of a surface and the degree of diffusion of the sound field resulting from its application, is questionable and needs a more systematic investigation taking into account the amount of scattering coefficient, the extension of this surfaces, the volume and shape of the room. The efficiency of the acoustic diffusers on the sound field, over frequency bands, could be observed through texture parameters ETx and Abs DBM, indirectly, and through SFD, directly. As future work, a new definition of the early decay time seems to be appropriate; the early decay time defined by the mixing time (EDTMt), which could be defined as the early decay time produced by the linear regression from the reflections amplitudes in the ITDG - Mt time interval.

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