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Scattering effects in small-rooms: from time and frequency analysis to psychoacoustic investigation

Lorenzo Rizzi[1] and Gabriele Ghelfi[2]

[1] Suono e Vita – Acoustic Engineering, Lecco LC, 23900, Italy
rizzi@suonoevita.it

[2] Suono e Vita – Acoustic Engineering, Lecco LC, 23900, Italy
ghelfi@suonoevita.it

ABSTRACT

This work continues the authors' effort to optimize a DSP tool for extrapolating from R.I.R. information regarding mixing time and sound scattering effects with in-situ measurements. Confirming past thesis, a new specific experiment allowed to scrutinize the effects of QRD scattering panels over non-Sabinian environments, both in frequency and in time domain. Listening tests have been performed to investigate perception of scattering panels effecting small-rooms acoustics quality. The sound diffusion properties have been searched with specific headphone auralization interviews, convolving known R.I.R.s with anechoic musical samples and correlating calculated data to psychoacoustic responses. The results validate the known effect on close field recording in small-rooms for music and recording giving new insights.

1. INTRODUCTION

This article extends the research [1, 2] carried out by the authors on the relationship between scattering and reverberation mixing properties in small-rooms. Non-Sabinian environments are rooms with small dimensions and heavy sound absorption, where Sabine's assumptions about diffuse sound field cannot be considered fulfilled. These rooms are de facto the place where nowadays music is recorded, mixed and produced. Music business dynamics moved most of the production phases to personal and project studios: this fact gives acousticians smaller 'cavities' to study and optimize. The main idea at the basis of this and other works [3, 4] realized by Acoustic Engineering Studio "Suono e Vita", is to in-depth knowledge of time and frequency domain properties of small acoustic spaces for music. It is necessary to underline that the approach of this research is different from the one used in other papers related to mixing time and mixing properties of rooms. Other research [5, 6, 7, 8] have dealt with mixing time for room reverberation simulation. This study has instead the objective to understand better non-Sabinian environments sound decay in order to optimize acoustic treatment of small-rooms for recording and rehearsing and gives practical help to sound engineers working with scattering panels.

1.1. Past research on diffuse field in real rooms

In particular, this research started in 2010 with the development of a DSP tool to study statistical properties of room impulse responses (R.I.R) in order to measure mixing time (t_{mix}), i.e. the time instant that divides early reflections from the diffuse field. Two different methods to study the statistical properties of impulse responses were selected in scientific literature [5, 6] and implemented in a DSP Matlab® tool developed by authors with appropriate changes. From the two approaches, the one proposed by Stewart and Sandler in [5] resulted to be more useful: their measure takes into account the kurtosis of the impulse response window and compares this value with the kurtosis of Gaussian distribution. When the distribution of the samples inside the window is Gaussian, the transition between deterministic early reflections and stochastic late reverberation can be considered accomplished. The time instant that marks this transition is the mixing time. Starting from experimental evidences, appropriate changes to these methodologies have been implemented and described in detail in [1].

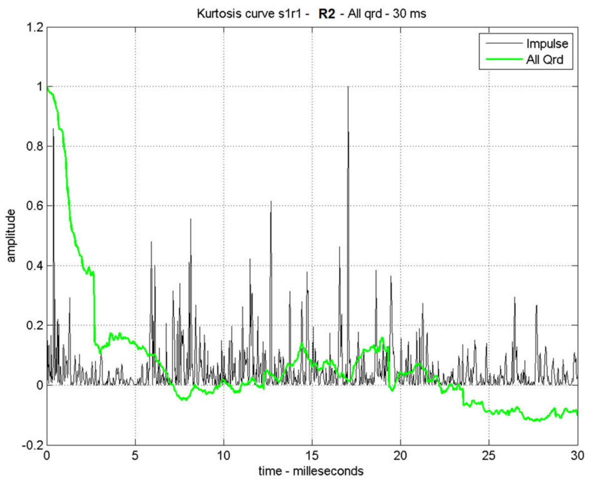

Figure 1 Example of plot of kurtosis curve (first 30 ms)

The tool has been tested on a variety of impulse responses, measured in various environments, different for dimensions, sound absorption characteristics and utilization. These tests show how measured t_{mix} values in small-rooms diverge considerably from theoretical ones, as expected. Ad hoc experiments have been carried out in order to study the relationship with scattering elements, using different amounts of QRD diffusers disposed inside non-Sabinian rooms for music. Evidences proved that a transition from deterministic to stochastic does still take place in these environments and it has also been proved how scattering helps to stabilize and modify this transition. It has been demonstrated that increasing the number of QRD panels the t_{mix} value decreases.

1.2. New experiment

In this paper the results obtained by a new experiment are reported: it has been specifically designed. With the goal of analyzing the behavior of the curves at different range of frequencies, the measured impulse responses has been high pass filtered. This allows to focus the analysis on the actual operative frequencies of QRD panels and to avoid panels diffraction effects and modal room behavior at middle and low frequencies [9, 10]. In this way only the scattering effect has been taken into account. This approach has been also extended to the two rooms analyzed for the previous article [1] and results have been compared. These elements show how the developed DSP tool is now ready for practical on-site utilization: it ensures the possibility to clearly verify the effect of the sound-scattering elements inserted inside a small-room for music.

1.3. Auralization and psychoacoustic test

A further step in the research was considered necessary: to verify if the improvements shown by the DSP tool, with modification of room scattering properties, have a psychoacoustic counterpart. Listening tests have been performed to investigate perception of scattering panels effecting small-room acoustic quality. Impulse responses measured for the present and previous experiments, where situations with different number of diffusing panels were compared. These room impulse responses have been convolved with anechoic musical samples: comparisons were proposed to a set of listeners with ABX tests and results are presented in this paper.

In section 2 a basic recap of the measurement methods and its statistical foundations will be reported. In section 3 the new experiment will be described, with its results and comparison with previous ones. In section 4 listening test setup and results will be presented.

2. MEASUREMENT METHOD

In 2010, two different methods to study the statistical properties of impulse responses were selected in scientific literature and implemented in a DSP tool developed by authors with appropriate changes. Of the two approaches, the one proposed by Stewart and Sandler in [5] has been preferred [1] because this method shows a better reaction to changes on room acoustical properties.

2.1. Kurtosis curve *k(t)*

Stewart and Sandler in their work [5] propose to use a measure of diffuse field Gaussian properties based on higher order statistics. They focus their attention on kurtosis (fourth order cumulant) for the following reason: if a set of random variables are jointly Gaussian, then all information about their distribution is in the moments of an order less than or equal to two; it can be interpreted that cumulants of an order greater than two measure the non-Gaussian nature of a time series or, stated otherwise, cumulants of Gaussian random processes equal zero for order greater than two. With this assumption, if the normalized kurtosis of the window impulse response is zero, it can be asserted that the distribution of the sample inside the window is Gaussian. Hence the kurtosis can be calculated (in its normalized version) with the formula

$$k = \frac{E(x-\mu)^4}{\sigma^4} - 3 \qquad (1)$$

where E( ) is the expectation operator, μ is the mean and σ^2 is the standard deviation. Kurtosis is calculated for each sliding window over the impulse response and the process creates a curve (called here *k(t)*). This curve, in its normalized version, starts with values around one and gradually goes towards zero as the degree of gaussianity of sample inside the window increases.

In Figure 1 and 2 examples of the kurtosis curve *k(t)*output, applied to impulse responses, can be seen. The black line shows the I.R. itself and the green line the kurtosis curve *k(t)*.

2.2. Methodology improvements and observation

All the methodologies found in literature present the problem of selecting the analysis window length. During our analysis, made on rooms with different dimensions and absorption characteristics, it became clear that there is no "perfect size" for the window size.

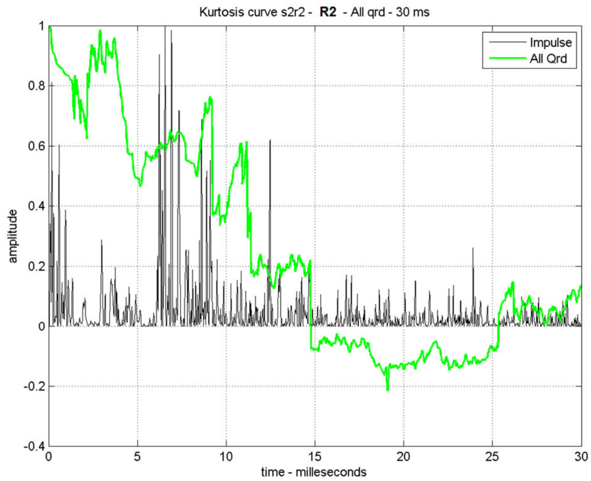

Figure 2 Example of plot of kurtosis curve (first 30 ms)

It is necessary to find a way to define window length related with the physical (not perceptual) characteristics of the room under analysis. It was proposed [1] to use a window length related to the concept of mean free path $\bar{l}$, i.e. the average distance a ray of sound travels inside a room before it encounters an obstacle [11]. The proposed window length is given by the following formula, where $\bar{l}$ is converted in [s]:

$$L_{win} = \frac{\bar{l}}{c} = \frac{4V}{cS} \quad [\mathrm{s}] \qquad (2)$$

where *V* is the volume of the room and *S* is the total surface area enclosing the room. In this way the presence of a set of reflections inside the window is ensured and furthermore it is extremely easy to calculate quantity strictly related with the room geometry: it results in longer windows for big rooms and shorter ones for small-rooms.

The curve *k(t)* based on kurtosis displays an interesting behavior: at some particular reflections during the I.R., very sharp discontinuities correspond. These discontinuities have a precise statistical meaning: discontinuity appears because the reflection is followed by a stochastic I.R. segment at least as long as the analysis window. In order to generate this phenomenon, the I.R. segment following the discontinuity reflection, has to contain only sparse reflections, lower in amplitude respect to the one that generated the discontinuity. In fact, in the first time instant where the outstanding reflection is no longer contained in the analysis window, the curve becomes Gaussian. These discontinuities are very useful to track changes in the acoustic space: i.e. their presence, indicate if the treatment on a specular reflection has been effective or not. In this aspect, the kurtosis curve behaves better than curve proposed by Abel and Huang [6] which was discarded.

Another behavior shown through the kurtosis curve, is the creation, inside small-rooms, of the "diffuser region" i.e. a portion of the room volume bounded by QRDs 2-D diffusivity geometrical polar responses, where the influence of sound diffusers is more effective. Inside this "diffuser region" every position of the receiver relative to the source becomes equivalent from a "reflection arrivals" point of view. It has also noticed how, by increasing the number of QRDs, the curves become more regular, more Gaussian: both this phenomena are expected in a diffuse field.

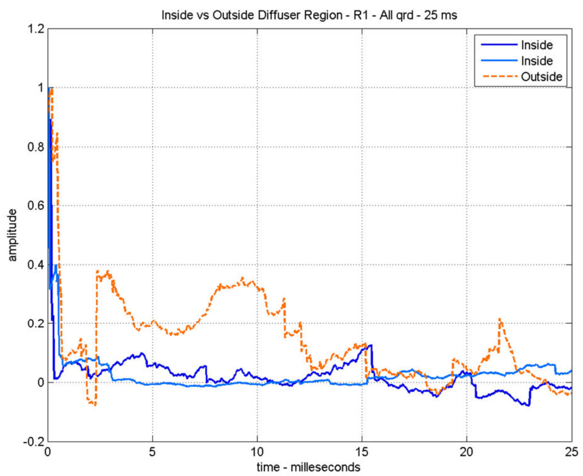

Figure 3 Kurtosis inside versus outside diffuser region.

For these reasons, the kurtosis curve *k(t)* proposed by Stewart and Sandler, with the modifications introduced, is now suitable for practical on-field utilization: it ensures the possibility to verify clearly the effect of the sound-diffusing elements inserted inside a small-room such as the reduction of strong specular reflections. This is shown by the linearization of the profile of the kurtosis curves calculated by the tool, displaying quickly the effectiveness of the scattering element presence. The new experiment described in the next paragraph has been designed in order to find new evidences.

3. NEW EXPERIMENT SETTING AND RESULTS

The experiment designed for this article was carried out inside an ordinary hard wall room (that will be called 'R1' from now on) with overall dimension *l, w, h* = 3.68, 3.53, 2.85 m. Inside the room there was no acoustic treatment and it was slightly furnished. Two types of QRDs were available: a QRD of dimension *l, w, h* = 0.5, 0.35, 1.00 m (indicated in blue in Figure 4) and 13 small QRDs of 0.08, 0.09, 1.00 m each (indicated in brown in Figure 4).

3.1. Experiment setup

Three different positions for the omni-directional measurement microphone (Earthworks M30) and two different positions for the source (an omni-directional dodecahedron loudspeaker produced by 01dB) were used: as can be seen from Figure 4 (where receiver position are indicated in green, and source position in red) are inside the so called "diffuser region", near to QRD panels.

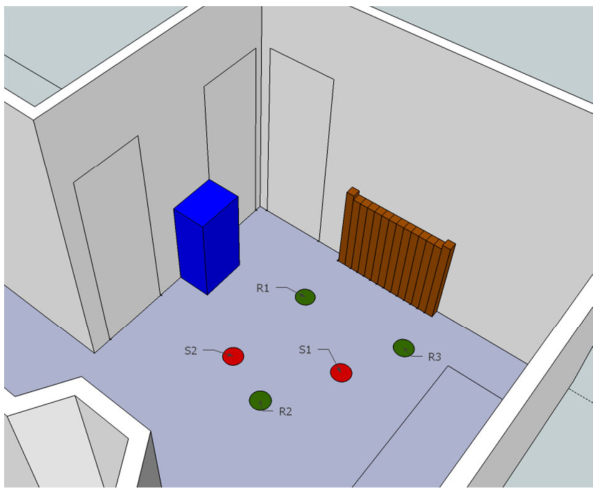

Figure 4 New experiment set up inside room R1

For each couple of source and receiver position an impulse response were measured with exponential sine sweep technique between 20 Hz and 20 kHz [17]. Sine sweep processing has been done using Aurora Plug-in Suite and kurtosis algorithm has been implemented in Matlab®. Different arrangement of sound diffusers has been tested in order to observe variations related to the number of panels: different impulse responses for each position have been measured for each diffuser setting, from no QRD present in the room to all available QRDs disposed inside the space. Source and receiver position have been carefully positioned in order to have the scattering panels working on first reflections. Each impulse response *h(t)* measured is compared with other *h(t)* measured in the same position. The overall number of panels is low because the new experiment setting has to be comparable with previous experiments, where the number of scattering panels was limited. Three cases have been finally taken into account:

- Set "**All**": all available QRD panels (blue panel and 13 brown panels) have been located inside the room (scattering surface, s.s. = 2 m^2);
- Set "**Half**": the blue panel and 8 brown panels have been located inside the room (s.s. = 1.5 m^2);
- Set "**Minimum**": no QRD panel was located inside the room.

3.2. Result analysis

In order to avoid problematic low frequency modes and to exclude diffraction effects (the "low-end" of scattering), the measured impulse responses have been high pass filtered at 500 Hz. Then the kurtosis curve *k(t)* has been calculated over filtered impulse responses. Figure 5 shows an example of results: the blue curve is the kurtosis curve for the setup with no QRD panel located inside the room. The red curve represents *k(t)* for the intermediate QRD setup, while the green one is *k(t)* for the situation with all QRD panels inside the room. Below each *k(t)* curve is shown the corresponding impulse response. The time interval considered here is 30 ms because, especially for non-Sabinian environments, the first part of the impulse response resulted most critical for room mixing properties: for a room like the one used in this experiment, with a Volume of 37 m^3, the average t_{mix} measured with kurtosis curves, is around 10 ms. The curves in Figure 5 show clearly how the presence of QRD panels helps to stabilize the curve profile also with the intermediate setting. The amplitude differences of reflections inside the impulse responses is a clear improvement given by scattering elements and the kurtosis curve is a useful tool to immediately quantify it. Also the great impulse response modifications that appear in the first few milliseconds (up to 7) are clearly traced by *k(t)* curve.

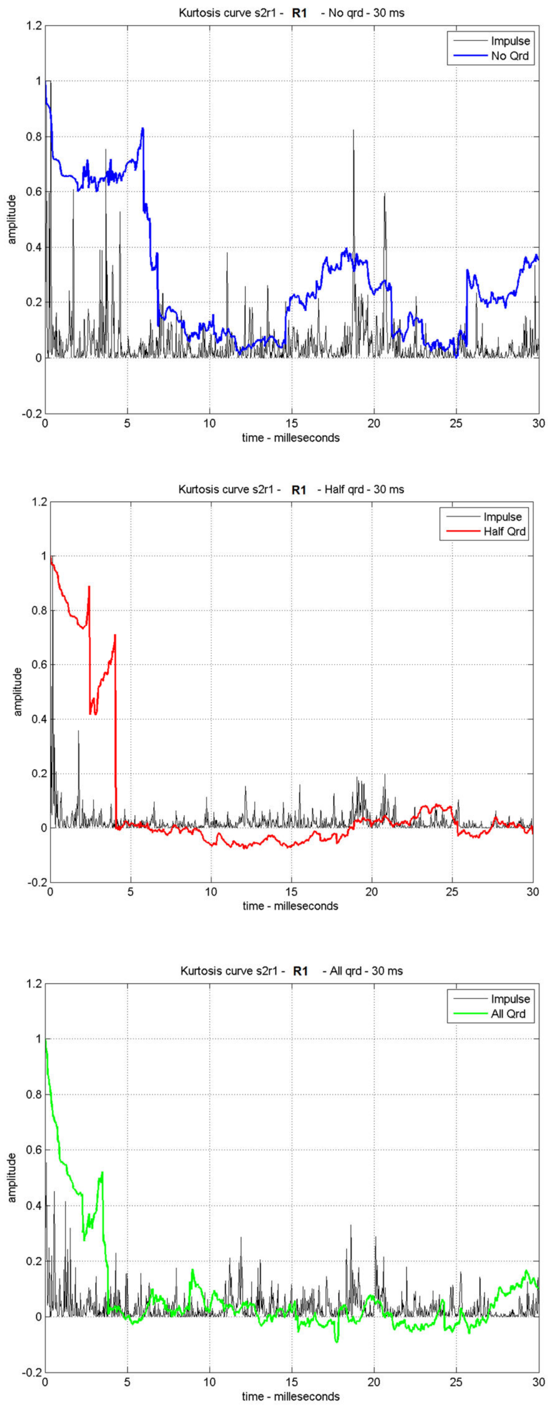

Figure 5 Examples of kurtosis curve plot with different QRD setup.

An overview of t_{mix} measured values remain useful and R.I.R. high pass filtering optimize its reading (small-rooms are strongly deterministic in the low frequencies region). Note that t_{mix} are compared after averaging between all the measured *h(t)*. Focusing only on scattering effects, the expected result is a clear reduction of t_{mix} values as the number of panels increases. The following table shows how this statement is actually verified.

QRD set	t_{mix} [ms]
All	10.5
Half	11.6
Minimum	17.8

Table 1 Average Mixing Time in Room R1

For non-Sabinian environments, the average measured values for t_{mix} are very different than theoretical one because standard model don't apply, but the presence of QRD panels certainly helps to make the sound field more diffuse, lowering mixing time. The effect is particularly evident for the first 7 milliseconds.

3.3. Comparison with other rooms

In order to verify the benefit of high pass filtering for the kurtosis analysis, the tool has been applied also to impulse responses measured in the two rooms previously analyzed. Briefly, room R2 is a small recording room of 51 m^3 of volume. In this room the QRDs are placed in two sides of the room facing each other. At one side there are three fixed QRDs while at the other side the QRDs were removable, so three different sets of measures were performed: the first one with no removable QRD (s.s. = 2 m^2), the second one with four QRDs (s.s. = 4.5 m^2) and the last one with six QRDs (s.s. = 6 m^2). Because of fixed QRD panels, for this room, a set with no panels at all could not be tested.

In the other room, ('R3') a rehearsal room with a volume of 109 m^3, three fixed QRD panels (two big panels and a small one) was present and three different sets of measures was arranged. In the first set a scattering surface of 6 m^2; the second set has been accomplished with both diffusers covered with absorbing and reflecting panels (s.s. = 1 m^2); the third set was an intermediate situation with scattering surface equal to 3.5 m^2. So, for each of the three rooms, a maximally diffusive set, an intermediate one and a less diffusive set can be compared.

	Min QRDs [ms]	Half QRDs [ms]	Max QRDs [ms]
R1	17.8	11.6	10.5
R2	12.4	10.8	10.4
R3	21.7	15.0	12.2

Table 2 t_{mix} comparison for the three rooms

In table 2 are reported the average mixing time values for the three different rooms, obtained from kurtosis curve applied over high pass filtered impulse responses in the three different cases.

From these results another evidence (Figure 6) of how the presence of QRD panels modifies mixing properties of the sound field is given: in room R2, where there is no a "zero scattering" situation, because of fixed panels, the reduction of t_{mix} is less evident than in the other two cases. The high pass filtering helps to observe mixing time modification in a more readable way, avoiding low frequencies problems.

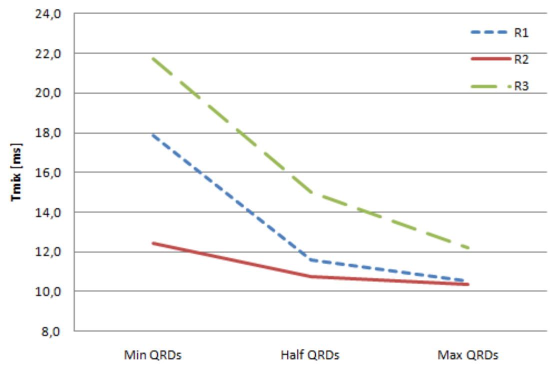

Figure 6 Decreasing values of t_{mix}

3.4. Comparison with ISO 3382 acoustical parameters

Other acoustical parameters (*EDT*, T_{20}) have been calculated for the measured impulse responses. Their values do not keep track of changes in mixing properties of the rooms. In the frequency range between 500 Hz and 16 kHz, very small modifications are measured.

In Figure 7 is shown the EDT graph for the three rooms in the three different scattering settings: it is clear that

t_{mix} is more useful in order evaluate QRD panels' action. For T_{20} an equivalent graph has been obtained.

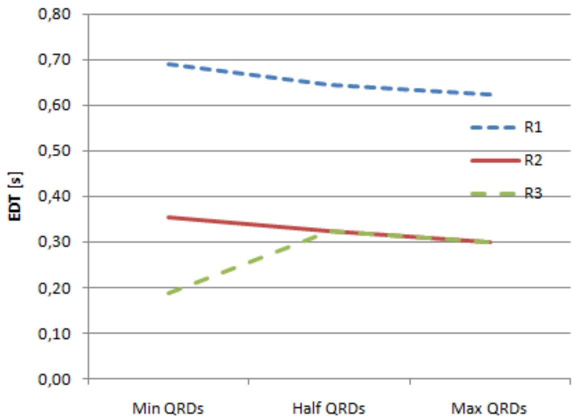

Figure 7 EDT values

4. LISTENING TEST

In order to verify if the improvements highlighted by kurtosis curves while changing the number of QRD panels have a perceptual counterpart, a series of listening test have been performed on a set of listeners with musical experience.

The main goal of the test is to understand if the presence of a relatively small amount of scattering panels can be perceived, comparing two short musical segments: one with the maximum amount of panels used in the experiment and one with the minimum. In order to make it possible, simple auralization techniques have been applied: short anechoic music samples have been convolved with real impulse responses measured in rooms R1, R2 and R3. For each room, a couple of source and receiver position has been taken into account. In this way, the listener had the chance to compare the music sample in two different sets of QRD panels' distribution.

Because of the goal of the research is to have a practical tool useful for in-situ measurements, all the test components are real ones: no virtual rooms or synthetic music sample have been used, but real impulse responses, measured from rooms used for musical purposes, and real anechoic music segments have been used.

ABX test procedure was chosen: the primary goal is to determine if the difference is noticeable or not. 8 second was the maximum length of music samples: this length has been chosen in order to have reliable comparison between different sets. Longer samples would not be appropriate because of listener short-term memory while shorter samples would not contain enough musical information in order to make a choice. The listeners were left unaware about test goals: just test execution mode was explained to them but no information about "where" to focus their attention (high frequencies, low frequencies, reverberation…) has been provided. All of them used the same listening setup (portable .wav file player, always set to the same volume, and AKG K530LTD headphones) and the chance to reply each single test, every time they needed, has been given to them. Qualitative analysis about this difference can be explored in further research. Two different test sessions was carried on: the first one on a small set of listeners in order to refine the test.

4.1. First session

The first test session was proposed to five selected listeners with musical experience. Two different types of music segments were proposed: the first one was represented by anechoic recordings of classical music while the second one was represented by anechoic recordings of percussion instruments (congas and bongos). ABX tests shown how, in case of classical music, the differences from setup with less scattering panels and setup with more panels were barely audible due to intrinsic nature of music material: long sustained notes combined with rich arrangements in 8 second samples do not contains enough information about room sound decay characteristics, making the choice more difficult. Percussive sounds, due to their impulsive nature, appear more suitable for decision making about this research goal (evaluation of non-Sabinian rooms sound decay). Moreover orchestral classical music sound very unnatural as it is "played" inside small rooms: low frequency modes distract the listeners with their "boomy" effect (remember that no information about "where" to focus listening attention has been provided to testers in order to avoid bias in decision making process). Percussive sounds result to be more suitable for the present research, especially the bongos' samples: the ones used for the test do not contain significant frequency content below 300 Hz, avoiding low frequency modes for the tested rooms. It is important to notice that, due to bongos frequency response, the QRD panels, which intervention range starts form 500 Hz, work over sound decay and not over instrument fundamental frequency. A proper selection of music material for listening test is crucial for its reliability as underlined by Wankling, Fazenda and Davies in [12]. After collecting testers' opinions and ABX tests results, the use of anechoic samples of bongos for all ABX tests was decided. Because of the listeners' difficulty in perceiving the differences between small delta of QRD quantity, it was decided to compare only the difference between maximum and minimum amount of scattering panels within each experiment.

4.2. Second session

The second test session was proposed to 16 listeners with musical experience. Each of them was asked to answer 12 ABX tests using always the same listening conditions: 4 tests have been prepared with auralization process between anechoic bongos samples (8 seconds length) and 2 different R.I.R. from room R1; 4 test have been prepared with anechoic bongos samples and impulse responses from room R2 and impulse responses from room R3 have been used for the remaining 4 samples.

4.3. Listening test results and discussion

ABX tests have given an overall rate of correct answers of 74%. This result needs to be analyzed by dividing the contributions from different rooms. Table 3 resumes results for each test. It is interesting to notice that auralization sample comparison for room R1 produces better results than the other two rooms while R2 produces the worst rate of correct answers. The R2 room poor results are essentially due to the fact that the comparison between sample A and sample B (maximum versus minimum presence of QRD panels) is done with a non-zero minimum: as reported in paragraph 3.2, in room R2 two QRD panels was fixed and the impulse responses for the minimum set have been actually recorded with these panels inside the room. Then the difference between two and six panels results to be hardly perceptible.

For room R1 instead the comparison has been done between a maximum QRD set and a "real" zero QRD set, giving better results. Room R3 has obtained average results (always higher than 50%) because the difference stressed in this case (sound diffusion versus sound absorption) is resulted less evident than the case where sound diffusion is compared with specular reflections (as in case of room R1).

It is necessary to stress the fact that the number of panels is limited respect to room wall surfaces: observing this fact, results obtained for room R1 show that the difference is perceptible.

Room	R.I.R.	Correct answers (%)
R1	s1r3	86%
R1	s1r3	71%
R3	s1r1	71%
R1	s2r1	71%
R1	s2r1	64%
R3	s1r1	64%
R2	s1r1	64%
R3	s3r2	57%
R3	s3r2	57%
R2	s2r2	57%
R2	s1r1	43%
R2	s2r2	36%

Table 3 Listening test results

In-depth analysis of room impulse responses and kurtosis curve profile shows that there is a relationship between good correct answers rate and attenuation of reflections in the first milliseconds (< 10 ms). Modification over early reflections induced by scattering panels appears to be perceptible, characterizing the acoustical quality of small rooms. The better results have also been obtained for impulse responses inside the so called "diffuser region". The QRD panels seem to have a perceptible effect when they can work locally in time and space. Direct impact on possible applications in acoustic treatment of small rooms is clear: their intervention is most effective when QRD panels are placed near both to the sound source and to the receiver.

Another important datum is that no relationship between linearization of the curve profile and perceptive recognition seems to be established. Correct answers rate below 50% has been resulted even for impulse responses where the curve profile linearizes after reaching diffuse field condition. This is an evidence, obtained studying statistical mixing properties of small rooms, of the well-known fact that early reflections are more relevant than the diffuse field from a perceptual point of view [16].

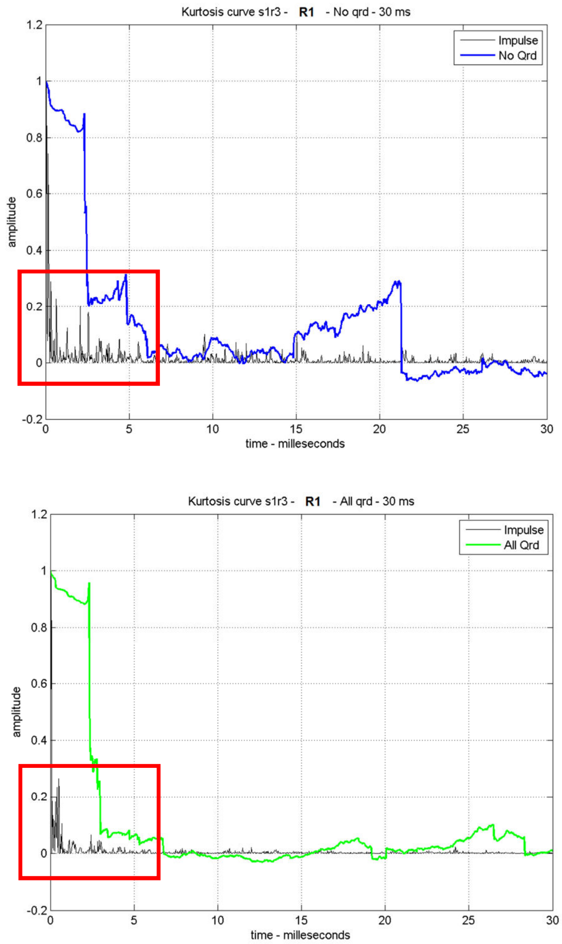

Figure 8 No QRDs (blue) vs All QRDs (green): note the different reflection amplitudes in first 5 ms.

5. CONCLUSIONS

The new experiment analysis confirms the conclusion of past research and demonstrates that the developed DSP tool for kurtosis curve generation is now ready for a practical on field utilization. The lack of sound decay analysis tools for non-Sabinain rooms makes the possibility to fill this gap more attractive. With high pass filtering of impulse responses, kurtosis curves and t_{mix} values profiles appear more useful. Modifcations about sound scattering properties of a portion of the room (diffuser region) appear immedetialy allowing acoustic designer and sound engineers to understand if a particualr intervention with scattering panels is effective or not.

Listening ABX tests were focused on understanding if the presence of a limited amount of scattering panels is perceptible or not, without dealing with qualitative analysis. Auralization tests have been made using impulse responses measured in real room and using anechoic recorded music samples, in order to avoid every synthetic shortcut, because the goal of the overall research is applicative. The best results have been obtained for a comparison between a “no-QRD” set and a “all-QRD” set, where the difference between strong specualr reflections and scattered ones appears more evident.

The results validate the known positive effect of scattering panels on close field recording in small-rooms for music and for recording giving new insights about sound decay in non-Sabinian environments. Local effects of scattering panels in time (reduction of early specular reflections) and space (diffuser region), highlighted by kurtosis curves, appears to have a stronger perceptual counterpart: the quality of multi-microphone-recording, even inside non-Sabinian rooms, can be increased taking into account this consideration.

Sound decay in non-Sabinian room is a research field still to be investigated: the increased importance of this kind of room in music business and the lack of analysis tools give to acousticians the challenge to better understand sound behavior in order to face and resolve problems that this kind of environments presents.

Next research should focus on perception of multiple first reflections against single ones.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] L. Rizzi and G. Ghelfi, “Measuring Mixing Time in non-Sabinian rooms: how scattering influences small-rooms responses”, 132nd AES Convention, Budapest, April 2012.

[2] L. Rizzi, G. Ghelfi, F. Nastasi and A. Sarti "Misura del tempo di miscelazione in ambienti Sabiniani e non Sabiniani", Associazione Italiana di Acustica, 38° Convegno Nazionale, Rimini, Giugno 2011.

[3] L. Rizzi and F. Nastasi, "Small studios with gypsum board sound insulation: a review of their room acoustics, details at the low frequencies", 124st AES Convention, Amsterdam, Netherlands, May 2008.

[4] L. Rizzi and F. Nastasi, "Room Acoustic measurements in non Sabinian enclosures for music: echometry, modal analysis, sound decay analysis", Internoise 2010, Lisbon, Portugal, June 2010.

[5] R. Stewart and M. Sandler, "Statistical measures of early reflections of room impulse responses", Proc. of the 10th Int. Conference on Digital Audio Effects (DAFx-07), Bordeaux, France, 2007.

[6] J.S. Abel and P. Huang, "A simple, robust measure of reverberation echo density", 121st AES Convention, San Francisco, CA, October 2006.

[7] A. Lindau, L. Kosanke and S. Weinzier "Perceptual evaluation of Model- and Signal-Based Predictors of the Mixing Time in Binaural Room Impulse Responses", JAES vol.60 no. 11 pp. 887-898, November 2012.

[8] J.M. Jot, L. Cerveau and O.Warusfel, "Analysis and synthesis of room reverberation based on a statistical time-frequency model", 103rd AES Convention, New York, 1997.

[9] L. Rizzi, A. Farina, P. Galaverna, P. Martignon, L. Corti and A. Rosati, "Surface scattering uniformity measurement in reflection free environments", 121st AES Convention, San Francisco, October 2006.

[10] L. Rizzi, A. Farina, P. Galaverna, P. Martignon, L. Corti and A. Rosati, "Scattering uniformity measurements and first reflection analysis in a large non-anechoic environment", 123st AES Convention, New York, October 2007.

[11] H.Kuttruff, "Room acoustics", Spon Press, London, 4th edition, 2000.

[12] M. Wankling, B. Fazenda and W. Davies "The Assessment of Low-Frequency Room Acoustic Parameters Using Descriptive Analysis", JAES vol.60 no. 5 pp. 325-337, May 2012.

[13] J.D. Polack, "La transmission de l'energie sonore dans les salles", Ph.D. thesis, Universitè du Maine, Le Mans, France, 1993.

[14] J.D. Polack, " Playing Billiards in the Concert Hall: the mathematical foundations of geometrical room acoustics", Applied Acoustics 38, pp. 235-244, Elsevier Science Publishers Ltd, 1993.

[15] G. Defrance and J.D. Polack, "Measuring the mixing time in auditoria", Acoustic 08, Paris 2008.

[16] S. Olive and F. Toole "The detection of reflection in typical rooms", JAES vol.37 pp. 539-553, July/Aug 1989.

[17] A.Farina "Advancements in impulse response measurements by sine sweeps", 122nd AES Convention, Vienna, Austria, May 2007.

[18] ISO 3382, "Acoustics – Measurements of room acoustics parameters", 2009.

[19] EBU Tech3276, "Listening conditions for the assessment of sound programme material: monophonic and two–channel stereophonic", 1998.