OBJECTIVE AND PERCEPTUAL EVALUATION OF ACOUSTIC SCATTERING FROM A VARIABLE-ACOUSTIC WALL IN A SMALL HALL

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1 INTRODUCTION

The positive effects of diffusive surfaces have incentivized their use in a broad number of concert halls[1]. However, these surfaces can bring to negative effects, such as the reduction of the reverberation time and the attenuation of the sound level[2]. Despite the aforementioned effects, the influence of the diffusive surfaces on binaural room impulse responses is still not completely clear. In order to understand the effects that a single diffusive surface has on acoustic parameters, an experiment has been conducted in a small concert hall with variable-acoustic. Monaural and binaural measurements have been performed.

The effects of sound diffusion on objective acoustic parameters have been investigated mainly in scale models. Kim, Kim, & Jeon[3] performed measurements in 1:50 rectangular and fan-shaped scale models and obtained the lower values *RT* and *EDT* when using audience diffusers, conversely they found that C_{80} increases. Jeon, Jang, Kim, & Vorländer[4] obtained results from scale model measurements showing that diffusers decrease early decay time (*EDT*), reverberation time (*RT*), and strength (*G*), but increase clarity (C_{80}). Suzumura et al.[5] have investigated how acoustical factors, such as the initial time delay gap (*ITDG*) and interaural cross correlation (*IACC*), vary in scattered sound fields affected by an array of circular columns used as diffusers. Ando[6] found that subjective diffuseness decreased as *IACC* increased. Takahashi & Takahashi[7] have found that, as the range of effective diffusivity in a frequency scale increased, the ratio of the perception of the difference between specular and diffuse reflections increases. The listening position is also an important factor since the subjective tonal effects of the responses increase when the listener gets closer to the diffuser. Very often auralizations in simulated concert halls are used to investigate the perceptual aspects of diffusive surfaces. Torres et al.[8] conducted listening tests to investigate the audibility of diffusion in auralized concert halls. Shtrepi et al.[9] determined the JNDs of diffuseness due to different scattering coefficients in an auralized shoebox-like concert hall.

In this study a small shoebox-like performance space has been used. Two different acoustic configurations of one of the long lateral walls have been considered. The effects of this surface have been studied through the analyses of the acoustic parameters, such as early decay time (*EDT*), reverberation time (T_{30}), clarity (C_{80}), definition (D_{50}) and interaural cross correlation (*IACC*), and through a perceptual evaluation, which aimed at determining the maximum distance from the lateral wall at which the acoustic scattering effects are still detectable.

2 OBJECTIVE MEASUREMENTS

2.1 Experimental room and measurements set-up

The acoustic measurements have been performed in a variable-acoustic environment, the Espace de Projection at IRCAM in Paris (Figure 1). The hall has a rectangular geometry (24 m x 15.5 m x 10 m), a capacity of 350 seats and a variable volume, which is achieved by varying the ceiling height[10]. In these measurements, the ceiling is set at its maximum height of 10 m. Each wall has four rows of panels (2.3 x 2.3 m), which are made up of three rotating triangular prisms. Six different

acoustic conditions can be assigned to the rotating prisms. The first level of panels can only assume two different configurations: reflective and absorptive. The absorptive condition was chosen for the lower level of panels in all the measurements, in order to avoid the strong reflections from the lower parts of the walls, as this configuration is not usual for an audience in a concert hall.
Two hall configurations were chosen in this study, so that the lateral wall could assume two different acoustic conditions: reflective and reflective/diffusive. The latter will be referred to as diffusive condition in the following paragraphs. A scattering coefficient of 0.7 averaged at 500 Hz and 1kHz could be estimated using BEM-based simulations performed with a prediction software named AFMG Reflex.

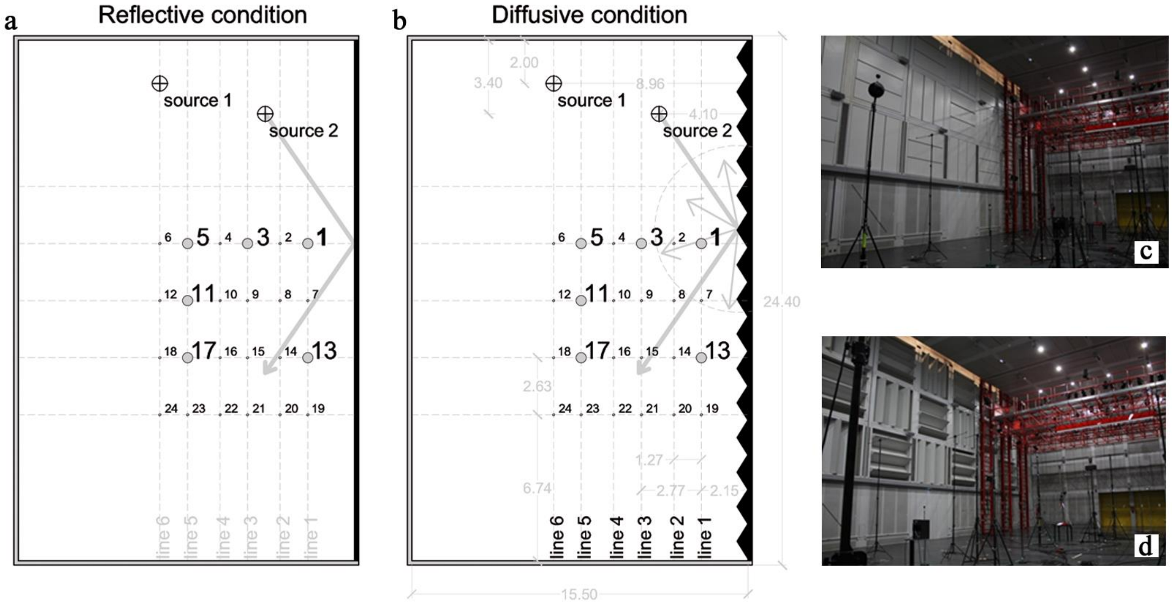

Figure 1: Scheme of the plan and pictures for the two acoustic conditions in the hall, i.e. reflective (a and c) and diffusive (b and d).

Twenty-four omnidirectional microphones Sennheiser KE-4 have been positioned in a crossed array that extended to one of the two halves of the audience area, and have been adjusted at a height of around 3.7 m from the floor level. Additionally, in three positions (1, 3 and 5) binaural measurements were performed by using an artificial head located at 3.7 m from the floor level.
Two omnidirectional dodecahedron loudspeakers were positioned on the front part of the room: the first was located on the central symmetry axis of the room and the second midway between the axis and the lateral wall. Loudspeaker, dummy head and amplifier were custom made devices by the Institute of Technical Acoustics, Aachen. Measurements and post processing has been carried out using the ITA-Toolbox, an open source toolbox for Matlab (http://ita-toolbox.org/).

2.2 Results

ISO 3382-1 (2009) has been used to measure the objective acoustic parameters: reverberation time (T_{30}), early decay time (*EDT*), clarity (C_{80}), definition (D_{50}), and inter-aural cross correlation (*IACC*). Figures 2 and 3 show the results of each objective room acoustic parameter as a function of the source-to-receiver distance, and as a function of the distance from the lateral wall (line 1, line 3 and line 5). Line 1 refers to the receivers closest to the lateral wall, while line 5 refers to those furthest from the wall, as can be seen in Figure 1. These four parameter values were averaged for the 500 and 1000 Hz octave bands. The following results have emerged:

- *EDT* decreased from the reflective to the diffusive configuration by more than 1 JND (JND_{EDT} = 5% of the lowest value of *EDT*, which in this case is about 0.05 s). The difference in the parameter values between the two configurations were almost constant with the distance from both source positions.

- T_{30} decreased from the reflective to the diffusive configuration by more than 2 JND (JND_{EDT} = 5% of the lowest value of T_{30}, which in this case was about 0.05 s). The differences in the parameter values between the two configurations were almost constant with the distance from source 1 and increased for source 2.
- C_{80} and D_{50} showed a tendency to increase, from the reflective to the diffusive configuration, by about 1 JND (JND_{C80} = 1 dB and JND_{D50} = 0.05). The differences in the parameter values between the two configurations were almost constant for the distance from source 1 and source 2.

Diffusive surfaces tend to disperse reflections in space, and since most of the surfaces in the hall were absorptive, *EDT* and T_{30} decreased. The differences between the impulse responses were mainly on the reflections density and intensity in its early part. This could led to higher C_{80} and D_{50} values. Various studies[2-5] have shown contrasting trends of different objective parameters that have made it impossible to define a general rule on the effects the diffusive surfaces on the room acoustic. It is evident that the acoustic parameter values depended above all on the presence of the diffusive and reflective surface and on the source-to-receiver distance. No significant differences were found for the distance from the lateral wall.

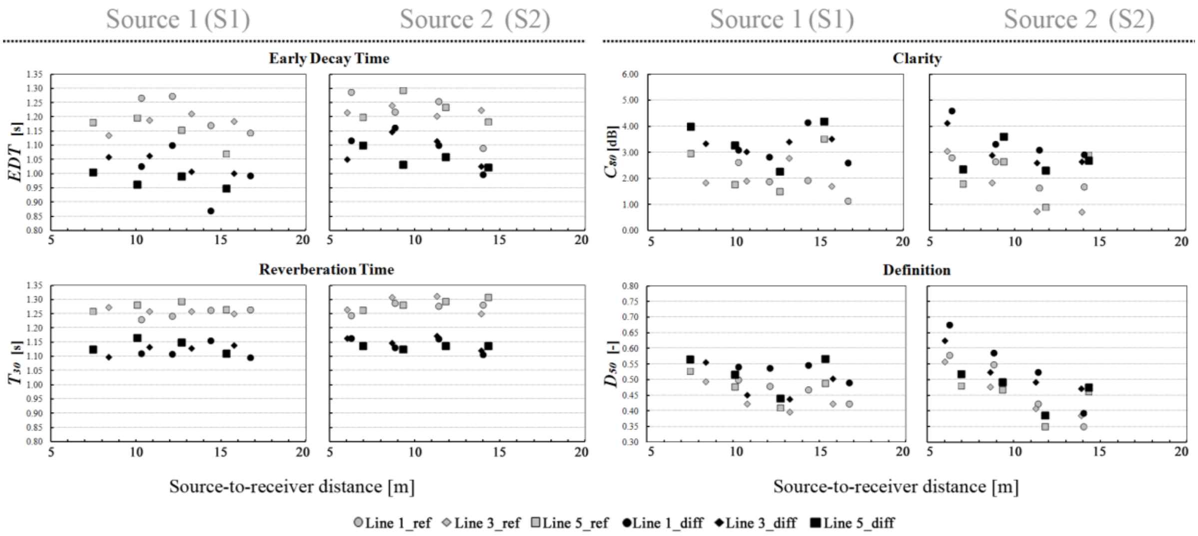

Figure 2: Early decay time (*EDT*), reverberation time (T_{30}), clarity (C_{80}), and definition (D_{50}) values versus source-to-receiver distance for both acoustic conditions of the reflective and diffusive test wall.

Figure 3 depicts the results of the investigation on *IACC*. This parameter has been evaluated through the early *IACC* and the late *IACC* values in both configurations of the hall. The values were averaged at 500 Hz, 1000 Hz and 2000 Hz.

- $IACC_{0\text{-}80}$ (Early *IACC*) did not change significantly for the two different wall conditions for either source position. The differences were within a JND_{IACC} value of 0.075. The parameter increased with the receiver-to-diffusive surface distance for both the reflective and diffusive conditions for the sources in positions 1 and 2.
- $IACC_{80\text{-}inf}$ (Late *IACC*) decreased in the diffusive condition for the receivers close to the lateral wall and the furthest from source position 1 by about 1 JND, while it did not change significantly for the two different conditions of the wall for source position 2. Increased with the receiver-to-diffusive surface distance for both the reflective and diffusive conditions for the source in position 1, while it increased for the positions close to the source and decreased at the furthest ones for source position 2.

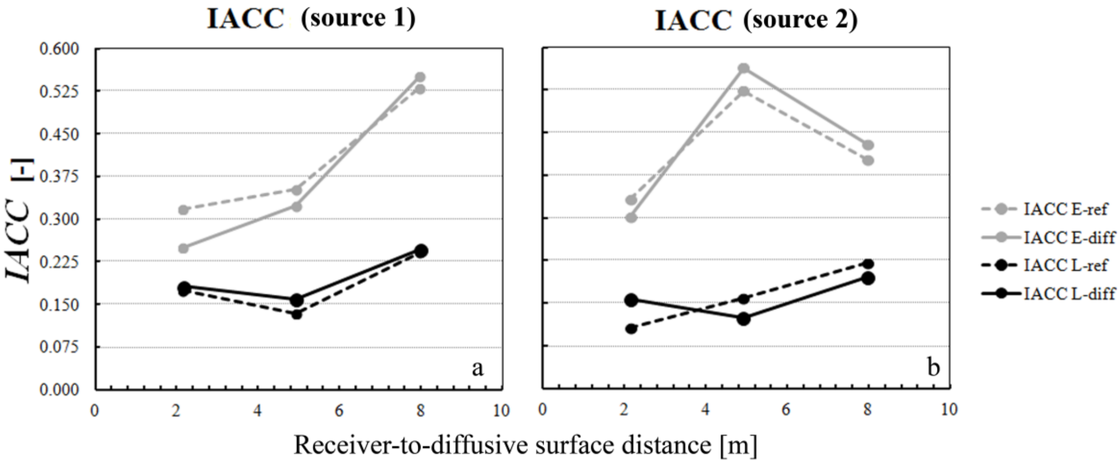

Figure 3: Early *IACC* (*$IACC_{0-80}$*) and Late *IACC* (*$IACC_{80-inf}$*) evaluated for source 1 and source 2. The values are given as function of the receiver-to-diffusive surface distance for each source position.

The influence of the diffusive surfaces proved to be related to the distance from the sound source for the *IACC* parameter, i.e. a lower correlation of the two ear signals was found at the positions close to the lateral wall and furthest from the source. This was due to the asymmetric condition created between the two ears, i.e. while the left ear was oriented toward the absorptive surfaces in all the conditions, the right ear was subject to changes between the reflective and the diffusive conditions[11].

3 LISTENING TESTS

Listening tests were organized in order to determine the perceptual threshold between two acoustic reflective conditions of a surface in relation to the receiver distance from the surface.

3.1 Method

A three-alternative forced choice (3-AFC) method was considered to be suitable for the listening tests. It is a special case of the family of m-AFC procedures originating from visual and auditory detection and discrimination research[12]. The collected data have been analyzed using Psignifit, which is a Matlab toolbox[13-14]. The method used for the analyses is based on Efron's parametric bootstrap technique, which is a Monte Carlo resampling technique relying on a large number of simulated repetitions of the original experiment. Different triads of the test signals were prepared at three positions in the audience area (1, 3 and 5) for the two different source positions, as shown in Figure 1. The triads included two different signals (R, for the reflective surface; S, for the diffusive surface) and were presented to the listener in randomized order (R-S-S, S-R-S, S-S-R, S-R-R, R-S-R, and R-R-S) for each position.

The listening session was conducted at Politecnico di Torino in a conference hall. The test has been performed by using open headphones (Sennheiser 600HD). The listening test consisted in a total of thirty triads, which were played to each listener. After listening to each triad (less than 18 s), the listener was asked to choose the sound signal that he or she perceived to be different from the other two. An illustrated explanation was given to each listener at the beginning of the test. Furthermore, to make them familiar with the signals, they were asked to listen to pairs of examples of the three music samples, which were played consecutively. The listeners were allowed to listen to the signals just once. They were not allowed to listen to the samples again, and did not receive any feedback on the possible correctness of their answers during the test. Furthermore, they were not allowed to take a break during the test, which lasted almost 20 minutes. In this way all the listeners performed the test in the same conditions.

3.2 Stimuli

The audio samples included three music motifs: a choral recording (“Alleluia”- Randall Thompson, St. Olaf Cantorei, Anechoic Choral Recordings, Wenger), a piano solo (“Ètude Op. 10 no. 4” - Frédéric Chopin, Renzo Vitale, Digital Recording) and an orchestra track (“Water Music Suite” - Handel/Harty, Osaka Philarmonic Orchestra, Anechoic Orchestral Music Recordings, Denon).

The audio samples length (5-6 s) was chosen to be long enough to give the listener enough time to assess the full extent of the sensation of the task and, at the same time did not bore those listeners who were familiar with the modus operandi.

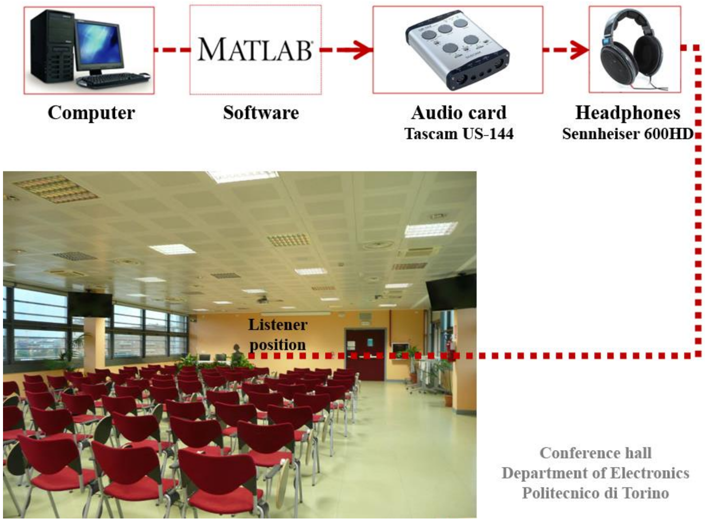

Figure 4: Listening set-up and venue (conference hall of Department of Electronics, Politecnico di Torino).

3.3 Test subjects

Thirty-one listeners participated in the test. They were made up of a group of research assistants and students aged between 25 and 30, who worked at Politecnico di Torino, Italy. An audiometric examination was performed in those listeners who had no information on their hearing abilities. An iPad-based application (uHear) has been used for this purpose. The output is shown in Figure 5.

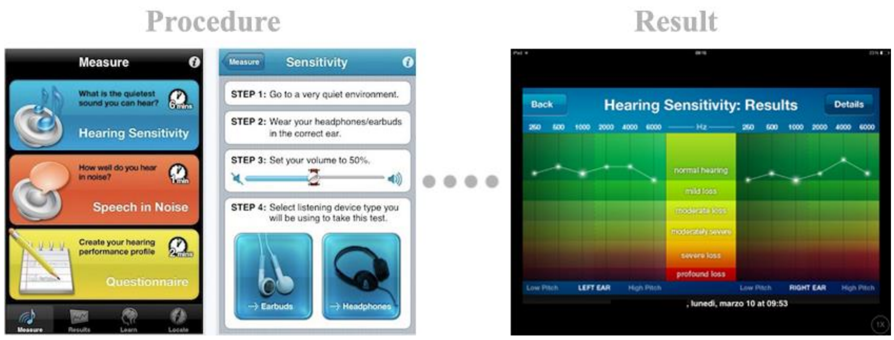

Figure 5: uHear user interface and the output result.

3.4 Results

Figure 6 shows the psychometric curve built out of the analyses of the psychoacoustical data. In this graph is given on the *y*-axis the probability of a correct answer, i.e., the performance level, as a function of the stimulus, and on the *x*-axis the stimulus intensity associated to the distance from the test wall. The black circles represent the data collected through the listening tests, i.e. the proportion of correct answers for a given stimulus.

Since the detection tests presented in this work are designed according to the forced choice criterion (3-AFC), the threshold is set to one half of the interval between the guessing and the lapsing rate; in this case, they are respectively equal to 1 and 0.33, resulting in a threshold value of 0.66[15]. Thus, the distance that corresponds to a performance level of 0.66 is the threshold distance. From this distance, the difference between the reflective and diffusive condition becomes difficult to detect. The results in Figure 6 show that the distance threshold is at about 1.5 m from the test wall.

Initially, a two-way analysis of variance (ANOVA) has been performed by using a statistical software named Minitab 17. The aim was to determine the significance of the different sound signals and source positions used in the experiment.

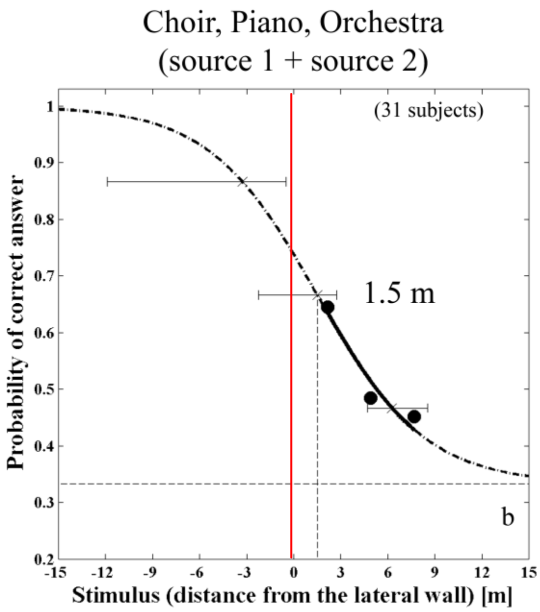

Figure 6: Psychometric function for 31 subjects. The black circles represent the data collected through the listening tests, i.e. the proportion of correct answers for a given stimulus, the solid line shows the best-fitting psychometric function assigned to the collected experimental data, the dashed line highlights the corresponding distance at which the probability of a correct answer was 66%, i.e. representing the distance threshold (1.5 m) at which the presence of the diffusive surface was no longer perceived, regardless of the source position or sound signal. The horizontal bars depict the confidence intervals, which show the variability of the psychometric function evaluated at 20%, 50% and 80% of the interval above the chance threshold which is equal to 0.33 (horizontal dashed line).

The ANOVA showed that the listening signal ($F(2, 26) = 1.25$, $p = 0.30$) and the source position ($F(1, 26) = 0.16$, $p = 0.69$) have no significant influence on the listening test result, i.e. no significant differences could be evaluated with a confidence level of 95% since the *p*-value resulted higher than 0.05. Therefore, the subjective data have been analyzed regardless of the source position or sound signal.
At the end of each test, the listeners were asked to comment on their experience. Most of the listeners declared that when playing the orchestra sample, the differences were easier to detect. The listeners stated that their task had been accomplishable, although they declared that they found

it very difficult to judge in some cases. The perceived differences were mainly in reverberation, and a some of the subjects noticed differences in sound level within each triad. These features were easier to identify for signals with a larger spectrum, such as the orchestra sample[9]. The attenuation of the sound level could be expected, as found also in Ryu and Jeon[2] and might have been further emphasized by the fact that the surfaces of the hall (except of the test surface and the floor) were set in absorptive mode. When using the reflective wall configuration, a strong specular reflection reaches the listener, conversely when setting the diffusive condition the sound energy is distributed in different direction and absorbed by the absorptive walls and ceiling.

Since most of the listeners were less sensitive to the presence of acoustic scattering at distant positions from the diffusive surfaces, the use of these surfaces in large concert halls might affect a small group of listeners and create a non-uniform audience area. This is in contrast with the objectives of the acoustic design of concert halls.

The listening tests could be improved by increasing the number of listeners, and by selecting stimuli with different spectral and temporal characteristics, e.g. single instruments. Furthermore, a new group of listeners made of professional musicians should be considered.

4 CONCLUSIONS

This preliminary research aimed at isolating the independent effects that a single diffusive surface has on the room acoustic parameters. A real-scale variable-acoustic environment was used for both monaural and binaural measurements, which were used to evaluate the objective and perceptual acoustic scattering effects. The acoustic conditions of the room under examination were ideal for the aim of this study. However, even if they might result unusual for a real concert hall, some considerations were made possible. The influence of the diffusive surfaces on the objective acoustic parameters was found to be more than 1 JND. Furthermore, this study provides evidence that the presence of acoustic scattering can be perceived by listeners in a performance space, and it was found that this perception is related to the distance from the diffusive surface, which could lead to uneven distribution of the acoustical quality in an audience area. Further, research on objective measures is needed to enlighten the causes of the perceived differences introduced by the presence of diffusive surfaces. Future work could involve testing of the influence of different diffusive surfaces characterized by different scattering or diffusion coefficients, located at different positions within the hall.

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