ABSTRACT

A mystery around perception of music in concert halls concerns the subjective perception of diffusing surfaces situated on walls and/or ceiling. Former studies have shown that listeners prefer diffuse conditions. Hence, further investigation on the audibility of diffusion in auralized concert halls has been necessary. The following research aimed to determine the threshold of hearable differences of the scattering changes in a virtual concert hall in two different positions of the audience area: one position next to the side wall and the other one close to the rear wall. Six different scattering coefficient values $s = 10, 30, 50, 60, 70$ and 90 % were assigned to the interior surfaces of the ceiling, side and rear walls in simulations carried out with three different software: Odeon® 10.1, Catt-Acoustic® v8.0 and Raven. The analysis has been performed by investigation of subjective perception of scattered sound in three sessions of listening tests by applying the 3AFC (three Alternative Forced Choice) method where stimuli were presented to subjects via headphones using signals auralized in the three software.

1 INTRODUCTION

Developers of software for room acoustics prediction aim on reliability of calculated results, confirmed by sufficiently good fit with measurements. The scattering coefficient, among other parameters, enhances prediction accuracy and in many cases it is an essential component in an accurate model. This is valid mainly when simplifying the geometrical construction of 3D models
in order to reduce modeling and calculation time. In the first Round Robin test in 1995\(^1\), it has been proven that simulations which consider sound diffusion give more accurate values on the most important acoustical parameters. With an increased interest in auralized sound, based on room acoustic simulation a greater emphasis on diffuse reflection has been lent as well.

Two different measures of sound diffusion\(^4\) were introduced with somewhat different applications: the first one called “scattering coefficient” gives the quantity of scattered reflections, and the other one called “diffusion coefficient” is intended for evaluation of the quality of sound diffusers. A scattering coefficient is a measure of the amount of sound scattered in a different direction from the specular reflection and it plays an important role particularly in the late acoustical response. Further investigation has shown that the more appropriate quantity to be used in simulation software is the random incidence scattering coefficient, rather than the uniformity diffusion coefficient\(^5\).

A “mystery” around perception of music in concert halls concerns the subjective perception of diffusing surfaces on walls and/or ceiling. There is some evidence that listeners prefer diffuse conditions\(^6\). Hence, further investigation on the audibility of diffusion in auralized concert halls was carried out through listening tests, where simulated binaural signals with frequency-dependent changes in surface scattering were compared showing not only the importance of diffusion in simulations as listeners declared a perceived difference, but also the importance of a frequency dependent scattering. It has been found that lateral wall diffuser can improve the auditory preference in the front and the sides of stalls\(^6\). Further, the influence of sound pressure level was found to be a dominant parameter to judge perception of scattered sound in a rectangular concert hall\(^10\). Just noticeable difference of scattering coefficient in auralized concert halls has been investigated in Vitale et al.\(^11\) through auralized signals in three different prediction tools as well.

In this paper, the characteristics of the scattered sound has been investigated through listening tests applying the 3AFC method\(^2,3\). The aim of this work is to determine how sensitive listeners are to changes of the scattering coefficient selections in simulated sound fields. Auditory experiments were performed with 36 auralized music samples with normalized impulse responses and the scattering parameter effectiveness was discussed through the listening test results.

## 2 SIMULATIONS

### 2.1 Prediction tools

Simulations were performed with three geometrical acoustic (GA) based software: Odeon\(^\circ\) 10.1, Catt-Acoustic\(^\circ\) v 8.0. and Raven. Odeon\(^\circ\) 10.1\(^13\) uses a hybrid calculation method, where early reflections are calculated by using a hybrid Image Source Model with stochastic scattering process using secondary sources, while late reflections are calculated by using a special ray-tracing (RT) method, where the secondary sources are assigned with a frequency-dependant directionality, the so-called “reflection-based scattering coefficient”. The secondary sources may have a Lambert, Lambert oblique or Uniform directivity, depending on the properties of the reflection as well as the calculation settings. Catt-Acoustic\(^\circ\) v 8.0.\(^14\) combines the Image Source Model (ISM) for calculation of the early reflection, and special ray-tracing with randomized Tail-corrected Cone-tracing (RTC) for full detailed calculation. Diffuse reflections in the late part are handled by randomizing the direction of reflected rays according to the Lambert’s distribution law\(^15\). The implementation of these scattering techniques is subject to changes in the new versions of Odeon and CATT-Acoustic. Raven\(^16\) combines an Image Source method for the realistic representation of early specular reflections with a stochastic ray-tracing approach to
model the diffuse, scattered reflections in the late part of the room impulse response. It uses an enhanced method which combines principles of RT and Radiosity called "Diffuse Rain".¹⁶⁻¹⁷

### 2.2 Case Study

A small music concert hall of about 480 seats, designed by ONLECO s.r.l., Turin (Italy) was considered in this investigation. Its geometry is similar to a 'shoe-box' characterized by a volume of $V=2380\,\text{m}^3$ with a simple rectangular plan (17 x 30m x maximal height of 7m) and a tilted audience area (Figure 1). It is slightly asymmetric as the stage position is not central to the symmetry axis. The stage has a simple geometry (5.5 m x 13.5m) and is elevated from the floor plane of 0.8 m. The audience area is divided in two smaller areas by transversal corridors with an oblique configuration. The ceiling is interrupted by two crossing beams in the central part and above it, stands a skylight window which was not considered in the 3D hall's model.

![Figure 1: Hall’s 3D model (left) and set-up (source and receivers positions) as used in the simulation (right). Receiver 3 and 15 were used as listening positions for the listening tests.](image)

### 2.3 Simulations set-up

A simplified 3D-CAD room model was provided to run the software simulations. The audience area was modeled as a "box", 0.8 m high and the same set-up of source-receivers was used in the different simulation models: a simple omnidirectional source, with a sound power level of 90 dB, was placed in the center of the stage at 1 m distance from the front border, at 1.5 m above the stage floor and far enough from the side walls to make sure the preservation of the source’s features. Fifteen listener positions were simulated considering a crossed evenly spaced array distribution of 3.8 m x 4.3 m, and extended to one of the two symmetric halves of the audience area. The receivers were positioned at a height of 1.2 m from the floor level under each seat i.e. 0.4 m above the box upper plan. The hall was considered in an unoccupied condition and the material properties, such as sound absorption coefficient and scattering coefficient, were defined for each octave band frequency and assigned according to the project documentation. Six simulations were performed in each software, varying the scattering coefficient values of the side and rear walls, and ceiling as shown in Figure 2 ($s = 10, 30, 50,$
60, 70, 90% assumed as averaged values of scattering coefficient\textsuperscript{13} at mid frequencies of 500Hz and 1000Hz). For CATT-Acoustic and Raven, simulations were run also with frequency constant scattering as it was possible to select input data for 125Hz-8kHz octave bands. These auralizations were analyzed in two different sessions of listening tests. In order to enable the comparison between alternatives, the same boundary conditions such as absorption coefficients, air temperature and relative humidity were considered for all the simulations, and the same settings (transition order, number of rays), type of source and receiver, and source-receivers’ positions were kept (Figure 1, right).

![Scattering coefficient](image)

**Figure 2**: Scattering coefficient curves s=10%, 30%, 50%, 60%, 70% and 90% corresponding to averaged values at mid-frequencies $s_{500Hz}$ and $s_{1000Hz}$

### 3  SUBJECTIVE ASSESSMENT OF SCATTERING COEFFICIENT

The objective evaluation of the scattered sound has been already presented\textsuperscript{22}. The following part of the research aims to determine the threshold of audible differences of the scattering changes in the room, in two different positions in the hall. The 3AFC (three Alternative Forced Choice) method\textsuperscript{2,3} was considered as suitable for the listening tests procedure. The audio experiment of three signals comparison test consisted of three stimuli, where two were identical samples assumed as the anchor sample and the third was the different one (Figure 3, right). Thirty experiments were played and for each of them three signals of the same track were run one after each other. At the end of the listening (18 s) the subjects were asked to answer: *Which sample was different?* The scattering values increased from 10% to 90% at mid frequencies for frequency dependent scattering auralizations and in all frequencies for the frequency constant scattering, where the 90% scattering samples were used as anchor values. Two receiver positions were considered (see Figure 1, right): one close to the side wall, almost in the middle of the audience seats of line 1 (receiver 3) and the other one near to the rear wall, central to the last row of seats (receiver 15). From the former analyzes of the different scenarios, these positions presented higher differences in the objective parameters values.
### 3.1 Stimulus Preparation

The stimuli were created by convolving the binaural impulse responses obtained from Odeon, CATT-Acoustic and Raven simulations, with three samples of anechoic music recordings. Three important criteria were considered when creating the impulse response for the simulator such as standard objective parameters should be within the range found in actual concert halls and within the known range of preferred values, and the simulator should sound natural with no disturbing effects such as echoes. The choice of the piece of music is a sensible aspect. The most important criterion for the choice of the motifs was hence the plausibility of the listening impression. The influence of the length of the motif was also considered. The samples were chosen long enough to give the subject enough time to assess the full extent of the sensation and, at the same time, short enough not to bore the listener if he or she had reached a conclusion long before the end of the motif. A length of almost 6 s turned out satisfactory for the needs of new listeners and did not overstretch the patience of listeners familiar with the modus operandi. The three samples represent a choir singing an alleluia (“Alleluia” - Randall Thompson, St. Olaf Cantorei, Anechoic Choral Recordings, Wenger), a solo instrument piano (“Étude Op. 10 no. 4” - Frédéric Chopin, Digital Recording) and an orchestra track (“Water Music Suite” - Handel/Harty, Osaka Philharmonic Orchestra, Anechoic Orchestral Music Recordings, Denon).

As described in the simulation set-up, the source chosen was an omnidirectional one and although a motif featuring a full size symphony orchestra promises a broad band signal energy it probably marked an unnatural listening situation as the orchestra’s sound was originated from a single point. This turned out to influence the listeners’ spatial impression. Though, as reported also in Torres et al. omnidirectionality is acceptable in this case, as the main goal is to create impulse responses with varying diffusivity, not to exactly replicate the instruments in the hall. This might have influenced the sound perception since coloration differences are perceived more consistently than changes in spaciousness.

The motifs offer substantial signal energy in the frequencies reaching from 80 to 500 Hz for the choir, from 70 Hz to 2 kHz for the piano track and 70 Hz to 4 kHz for the orchestra sample. To exclude the effects of loudness, all audio samples were adjusted at the same level. The samples were played in the order presented above, which was a choice aimed to the gradual training of the listeners as the difficulty of the signals increased.

![Figure 3: Simulations’ scheme (left) and Listening test scheme (right)](image)
3.2 Experiment Arrangement

The listening tests were carried out in three different moments for the three software. First, the Odeo tests were organized at the Virtual Reality Laboratory at the Institute of Technical Acoustic - ITA (RWTH, Aachen). The setup consisted of one computer position, a high quality sound card (RME) and headphones system (STAX -SRM-1/MK-2). The CATT-Acoustic and Raven tests sessions were organized at the Politecnico di Torino, in three different environments judged as silent ones: in the Library of Energy Department, in a large classroom and in an office. The choice of the test location was influenced by a preliminary analyzes of listener preferences of a smaller space which turned out to help them concentrate better on their task. In this test was used the same setup, but this time the headphones that we used are the Sennheiser 600HD and the sound card is a Tascam US-144 MKII.

All participants were familiarized with the test by an illustrated explanation of the test's steps and in order to give them a vital impression of their task, pairs with examples of the three signals were played consecutively. Subjects could not listen to these samples again or switch between them, nor were allowed to listen to the experiment again and received no feedback about the possible correctness of their answer which was considered to be important, as it was ensured this way that each participant could come to his or her conclusion based on exactly the same testing procedure.

The number of participants is shown in Table 1. Sixteen listeners for the Odeo session, twelve and fourteen for the CATT-Acoustic sessions and, fourteen and nineteen for the Raven sessions passed the consistency test. The listening test consisted of 3 groups of 10 experiments for each stimuli. Participants could not take breaks during the test which lasted less than 20 minutes for each listener. After the test, the comments on their difficulty were collected.

<table>
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<tr>
<th>Table 1: Listening tests participants</th>
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<td>ODEON</td>
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<td>Total nr. of participants</td>
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<td>After consistency test</td>
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*Odeon session:* The participants stated that their task was difficult as some samples couldn't be judged with some certainty, but about 50% could be rated with some confidence. All test participants, however, stated that their task was accomplishable and that they recognized the aspect of the sample they were to judge. The group of test listeners (25 to 30 years old) was composed of assistants and students of ITA.

*CATT-Acoustic and Raven sessions:* In both, participants stated that their task was very difficult and that less than 50% of the experiments could be rated with some confidence. The group of test listeners (25 to 45 years old) was composed of assistants and students of Politecnico di Torino. In all the tests subjects were willing to participate in listening tests.

3.3 Listening Test Results

The data gathered consisted in a series of matrixes for each listener, containing their choice on the alternatives presented for each experiment, where to the correct answers were assigned a value of 1 and a value of 0 to the missed ones. This data were later elaborated and psychometric functions were built using the software Psignifit 2.5.6, a toolbox for Matlab application.

Figures 4 and 5 depict the result of this analysis which consisted in a comparative approach between the psychometric functions concerning the two positions in the hall and the
psychometric functions for each of the three samples. They show the probability of correct answer, i.e. perception of differences, in function of the stimulus variable intensity. These graphs are built by first determining the lower bound $y$ of the curve which represents the base rate of performance in the absence of a signal and the upper bound $(1 - \lambda)$ of the curve that is the performance level for an arbitrarily large stimulus signal, where $\lambda$ corresponds to the rate at which observers lapse responding incorrectly regardless to the stimuli intensity. As the chosen paradigm is a 3-AFC method, for each of the three signal corresponds a base rate of $y = 0.33$ which determines the lower bound. The upper value of the curve does not exceed the value of 1, which is the value correspondent to a rate where the observer doesn't lapse responding incorrectly at a certain stimulus intensity which, in this case, refers to $s = 10\%$. For position 15 and the piano sample, the value of $\lambda$ resulted to be different from 0, showing a performance level lower than 1 for the largest stimulus signal. Slopes and thresholds of the curves were compared as well, and as shown in eq. (1) $JND$ values were determined as a difference between scattering coefficient value chosen as anchor ($s_{\text{anchor}} = 90\%$) and the value of scattering correspondent to an approximately 66% of correct performance:

$$JND = s_{\text{anchor}} - s_{66\%}$$

Odeon session: The founded $JND$ values vary for the two positions and for the three different samples. This results show not only the importance of the samples' choice, but also the importance of the experiment conditions as the two positions were chosen close to the side and rear walls, respectively. There is a difference of 5% in $JND$ value between the two positions, which shows that listeners close to the side walls can hear lower differences of scattering changes (Figure 4). The two curves have almost the same slope for $s_{66\%}$, which assigns almost the same degree of uncertainty to the determination of the $JND$ value. The psychometric curves describing the behavior of listeners for the three different signals (see Figure 5) showed three different values of $JND$. For the choir and the orchestra samples these values are higher, i.e. larger differences of scattering are audible by listeners if this samples are played. Even though the $JND$ value for the choir is 3% lower than the orchestra's corresponding value, the uncertainty of $JND_{\text{chor}}$ is lower as the slope is higher. The piano sample resulted as the one with a fairly elevated degree of difficulty which was confirmed by the listeners' answers at the end of each test. This psychometric curve presents a higher slope and lower performance level compared to the other two signals results.

![Figure 4](image-url)
represents the probability of correct answers for each of the stimuli intensity, the solid line shows the best-fitting psychometric function assigned to the experimental data collected, the red and black dotted lines highlight respectively the $s_{66\%}$ values and anchor value ($s = 90\%$), the box-plots represent the statistical distribution of the simulated data.

Figure 5: Psychometric function for three samples (data averaged for each listening position): (1) alleluia choir, (2) piano solo and (3) orchestra.

CATT-Acoustic and Raven sessions: These two sessions results showed that was not possible to define the scattering thresholds for different tested positions and samples since, except for the orchestra samples in CATT-Acoustic (see Figure 6), the averaged subjective responses of the tested subjects were below the performance of 66% of correct answers, thus was not possible to determine a difference limen. As was reported above, the orchestra signal had larger spectrum which explains the different coloration effects perceived for this sample. However, listeners seem to be more confident in the tests where frequency dependent scattering was employed.

At the end of each test listeners were asked to comment on their experience. Perceived differences were clearly dependent on the input signals. Principally they ranked the samples according an increasing perceived difficulty: 1) orchestra, 2) choir and 3) piano sample. Where was possible, they perceived changes in the frequency coloration and just a few noticed difference in reverberance. However no feedback on sound preferences could be gathered.
4 CONCLUSIONS

In this study, six alternatives in a virtual concert hall model have been simulated with three acoustic prediction software, based on variations of scattering coefficient values applied to the ceiling, side and rear walls. Though the importance of the scattering modeling in terms of simulation accuracy is known, a detailed impact of sound scattering on simulated objective room acoustic parameters has been further investigated. This test has been performed with three different calculation algorithms used in software ODEON®, CATT-Acoustic® and RAVEN. The subjective assessment of frequency dependent and frequency constant scattering perception has been investigated through listening tests applying the 3AFC method, where stimuli have been presented to subjects via headphones by using auralized signals. Subjects were asked to identify whether or not audio stimuli were perceptually identical by choosing the different perceived signal. Statistical analysis has been carried out and psychometric functions have been built, and thresholds, slope and performance levels have been compared for two positions in the hall and three types of signals. Different JND-s values have been determined for the two listener positions and for the different motifs played in the Odeon listening test. These results were coherent with the degree of difficulty expressed by listeners for each sample played. It has been found that scattering perception is dependent either on the signal chosen and localization of the position in the hall. Raven and CATT-Acoustic

As listeners are not sensible to differences of scattering values below the JND, it should be easier to limit and intensify resources in a specific range of scattering magnitude. Therefore, this JND values are to be translated in terms of economical and time expenses in the design process of diffusers. Some improvements of the tests could be done, such as considering a multiple source ensemble with more realistic directivities as suggested by Torres et al. 7, increasing the number of participants to the listening test and selecting different type of signals. Based on this preliminary study, future works may lead to the investigation of the objective acoustical parameters and subjective listener responses in a larger number of halls, and not only virtual halls but also in real ones, based on in-situ measurements or scaled models. While the method described in this paper is designed for concert halls with comparable dimensions to the hall examined, it should be investigated in differently sized and shaped concert halls as well. Would be interesting to investigate if considering a different anchor value would bring to the
same results. However, it is necessary to develop in-situ diffusivity evaluation method to enable comparison with simulated sound fields including frequency dependent scattering, since they are an approximation of the actual sound fields in concert halls. First, it should be investigated the audibility of scattering effects in real halls and difference limens should be determined. For these spaces.

ACKNOWLEDGMENTS

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