An experimental evaluation of the impact of scattering on sound field diffusivity

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This work provides a systematic experimental evaluation of the impact of scattering on sound field diffusivity in a proportionate medium-small sized room. A scale model is set up in many ways by increasing the amount of scattering, and detailing measurements of the reverberation time in each case. With the aid of statistical tools, the role of scattering in the process of achieving a diffuse sound field from initially non-diffuse conditions is outlined and a set of reference scattering threshold values is derived. It is found that the same values ensure the validity of the Sabine formula when corrections are adopted in its application. Reverberation time is also predicted in non-diffuse conditions by the Nilsson approach, and its performance is systematically compared with measurements. The Nilsson method was a better predictor of reverberation time under non-diffuse conditions than classical reverberation time formulas. However, for diffuse sound fields, the same method tended to diverge from measured values. An application using more realistic room conditions is developed together with computer simulations. The results outline that there is limited benefit to using computer-aided design models instead of simple formulas to predict reverberation time for non-diffuse sound fields in proportionate medium-small sized rooms.

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I. INTRODUCTION

Over the years, using the scattering coefficient together with the sound absorption coefficient in order to improve the accuracy of room acoustics predictions has become increasingly common. Nowadays, room-acoustical simulation programs require both coefficients to describe the surface properties and, more recently, a formula for the reverberation time where the scattering values are needed as inputs was also proposed.[1] Despite the large number of works on scattering (for reviews, see Refs. 2 and 3), its effect on the physical nature of the sound field (diffuse or not) has not been properly investigated from the experimental point of view. As outlined below, this will be the main purpose of this work.

In fact, most of the previous relevant literature on the role of scattering in the sound field is concerned with more specific problems such as the choice of suitable values of the parameter in computer simulations. For instance, in Ref. 4, ray tracing predictions were compared with scale model measurements for a group of large rooms, while in Refs. 5 and 6 a scattering value close to 0.1 for plain walls was found to be generally appropriate for matching computer simulations and scale modeling of auditorium type rooms with a quasi-cubic shape. A few years ago some partial numerical and experimental results were achieved[7] regarding strategies to compensate for the lack of diffusion by means of sound scattering.

A framework to match the diffusion of the sound field with the surface properties was presented in a recent theoretical paper.[8] In this work, the first condition set by the author is a mean free path in a room equal to $4V/S_T$, which corresponds to the presence of oblique waves only (hereafter referred to as "non-grazing") and was demonstrated in the past to be valid only in rooms with diffusely reflecting boundaries.[9] The subsequent derivations outline the role of scattering and absorption in granting a certain degree of diffusion to the sound field. Computer simulations in large rooms are also developed to validate the theory. The best results are obtained for rooms where a more uniform distribution of the surface properties is found; in fact, these cases met the assumptions of the theory. The eventual presence of axial and/or tangential waves (hereafter referred to as "grazing" waves), which often are caused by a non-uniform distribution of the acoustical materials, cannot be accounted for in the model. Consequently, the impact of grazing waves on the diffusion of the sound field cannot be described by the theory.

Unfortunately, a review of the literature reveals that a complete experimental study on the impact of scattering on the sound field diffusivity is still lacking. Therefore, the first objective of this work is to measure systematically the reverberation time in the sound field while increasing scattering and absorption. This makes it possible to relate the amount of scattering and absorption with the buildup of diffuse conditions, which are monitored by the reverberation time and the spread of its values in the room. To these ends, the statistical test proposed by Davy[10,11] for the study of reverberation chambers is employed.

Another clear limit of the previous studies is their exclusive interest in large rooms. In fact, the deviations from diffuse conditions in smaller rooms are said to be more subtle and the impact of diffusing boundaries more difficult to evaluate practically.[12] However, medium-small size rooms are essential for a number of functions (among them classrooms,

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meeting rooms, small auditoria, etc.) and so specific information on scattering in this type of sound field would be valuable. To address this point, the present study will deal exclusively with a medium-small sized room with ratios 1:2:3. A 1:16 modular scale model of the room was set up in several ways by patching the interior surfaces with scattering and absorbing pieces. Suitable acoustical data for the patches were obtained by means of a scaled reverberation chamber[13,14] and by measurements of the model room. By doing so, the transition from non-diffuse to diffuse sound field conditions was traced and the role of scattering and absorption could be outlined.

Another task of this work is to test the formula developed few years ago by Nilsson,[15,16] who proposed a method to estimate the reverberation time in rooms where non-diffuse conditions are expected. The approach was conceived especially for rooms with an uneven sound absorption and resolves the problem of reverberation by means of a statistical energy analysis (SEA) system where the random incidence scattering coefficient enters as a parameter. Nilsson's main idea was in fact to consider the scattering as a coupling factor between the room modes, that is, between grazing and non-grazing waves. The balance between the mode types governs the sound field diffusion and the diffuse condition is achieved when the non-grazing modes prevail over the grazing ones. For this latter type of waves, an equivalent sound absorption is obtained by estimating the grazing absorption over those room surfaces that are presumed to be porous. Nilsson's theory was included in the EN norm[1] and was compared with other formulas and with computer simulations only.[17] The results showed that the method generally performed more closely to the computer simulations than did other formulas such as Sabine, Arau and Fitzroy. Unfortunately, until now, few experimental applications have been found,[18,19] probably due to the still limited availability of reliable scattering data which are needed to employ the model.

Finally, in the present study, a group of more realistic preparations for the scale model room is considered. The above concepts and formulas are applied and computer simulations are accomplished. This is done in order to focus on some of the most important applications in medium-small sized rooms, as for instance the field of classroom acoustics.

The work is organized as follows: in Sec. II the impact of the progression of scattering in a regular room is developed. The subparagraphs are organized to cover several related issues dealing with the experimental work, the buildup of a diffuse sound field, the validity of the classical Sabine formula, and the use of Nilsson's model. An outline on the effect of sound absorption and scattering is also presented in Sec. II F. In Sec. III, a normal room is studied using the same tools applied previously, and in Sec. IV a structured discussion of the findings is reported. Conclusions are in Sec. V.

II. STUDY OF THE INCREASE OF SCATTERING IN A REGULAR ROOM

A. Acoustical qualification of the materials

A 1:16 scale reverberation chamber was prepared to accomplish both sound absorption and sound scattering measures.

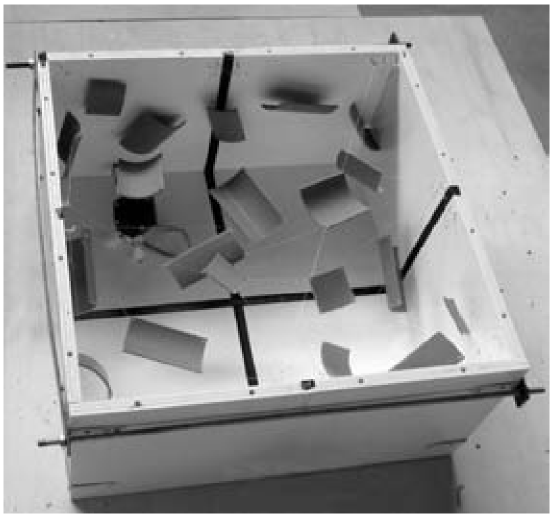

FIG. 1. View of the scaled reverberation chamber in the final operative configuration with reflectors installed. The floor can be changed to host a rotating central area having 5.6 m FS diameter which is flush with the rest of the floor and is attached to a rotating plate underneath.

The volume was 256 m^3 full scale (FS) and the chamber, whose interior is shown in Fig. 1, followed the advice on diffusing reflectors[13] in order to achieve suitable diffuse conditions in the room. The floor could also be prepared with a central round section flush with the rest. This 5.6 m FS diameter circular area was attached to a turntable underneath to implement the measurements of scattering.[14]

Different types of sound absorbing and sound scattering elements were prepared. Specifically, the latter consisted of small wooden pieces of varying dimensions and geometry (ranging from 0.16 m FS to 1.28 m FS), glued on a plastic grid in a random order. The scattering patch has a 4 m FS side and is varnished in order to limit its sound absorption. The scattering measurements were accomplished using a circular piece with a 5.6 m FS diameter. Sound absorbing samples were obtained by gluing one curtain layer on a 4 m FS side plastic grid. Figure 2 shows one scattering and one sound absorbing element. In the measurements of the interior varnish finishing absorption, a Perspex tile was used to reach the highest reference reverberation time at which point it was swapped with a varnished tile.

The measurement chain consisted of a 7 cm diameter piezoelectric dodecahedron with an amplifier, a 1/4-inch microphone with the related preamplifier, and a MOTU®

FIG. 2. The scattering (left) and absorbing (right) samples used in the setups of the model room.

TABLE I. Verification of the Davy criterion for the reverberation chamber. The Davy Criterion is met when the measured quantity is less than the theoretical value.

RC	Theoretical	Measured
125 Hz	5.9%	4.8%
250 Hz	4.0%	2.7%
500 Hz	2.9%	2.3%
1 kHz	2.1%	1.6%

Traveler (Cambridge, MA) sound card operating at 192 kHz sampling rate. This chain was used throughout the study. Impulse responses were obtained with a sine sweep technique and were collected by inserting the microphone through holes in the ceiling. The measured responses were processed by means of the B&K 7841 Dirac® (Naerum, Denmark) software in order to retrieve the full scale equivalent after compensating for air absorption and rescaling the time axis. The obtained signal-to-noise ratio ranged from 55 dB to 63 dB depending on the octave, thus allowing the calculation of T30 to characterize the reverberation time. Four source positions and 16 microphone positions were chosen for the reverberation chamber measurements.

First, the degree of diffusion in the chamber was optimized by testing several numbers and placements of the suspended reflectors. To test the degree of diffusion reached in the chamber, the Davy approach (see Sec. II C for its description) was used, as in Ref. 20, by employing the collected T30 data and the measured spatial standard deviations. The results, reported in Table I, showed that the reverberation chamber complied with the criterion in the bands 125 Hz–1 kHz FS. Despite the computer correction, the higher bands were dropped to avoid any relevant impact of the air absorption.

As it will be discussed, some further acoustical data were obtained from measurements in the scale model of the room. The complete data set of the acoustical properties of materials is reported in Table II. It is to be noted in Table II that, despite the varnish treatment, the scattering patches had a non-negligible sound absorption.

B. Setup of the scale model

A 1:16 scale model of a regular room with dimensions in the ratios 1:2:3 and FS dimensions 12 × 8 × 4 m was assembled. The aspect ratio was chosen on purpose not to be optimized according to the modal distribution in order to be similar to typical enclosed living environments whose dimensions are often fixed by non-acoustical criteria. The model was conceived as a modular structure with square plates of 4 m FS side. These plates were locked together to build the floor and the walls of the room. The ceiling was built in one piece and had 24 holes with stoppers for introducing a microphone. All of the interior surfaces, including the stoppers, were varnished to limit sound absorption and the minimal leakages between the plates were sealed with tape. The resulting structure was tight and rigid. The interior could be arranged in an extremely flexible way by patching the plates with either sound absorbing or sound scattering frames. This was done simply by suspending or appending a grid hosting the finishing to the ceiling or to the walls, or by laying the samples on the floor.

TABLE II. Sound absorption α and sound scattering δ data of the model surfaces. SRC: measured in the scaled reverberation chamber, SMR: measured in the scale model room to avoid edge effects. Bold data are those used in the study. Refer to the text (Sec. II D) for details.

α		250 Hz	500 Hz	1 kHz
Varnished surfaces	RC	**0.046**	**0.050**	0.06
	MR	0.036	0.044	**0.05**
Scattering patches	RC	0.120	0.180	0.257
	MR	**0.095**	**0.142**	**0.170**
Absorbing patches	RC	0.50	0.75	0.90
Audience	RC	0.47	0.66	0.81
δ				
Scattering patches	RC	0.20	0.50	0.75
Audience	RC	0.25	0.60	1.00

The basic experimental idea was to set up the model in a number of configurations having an increasing number of scattering frames. In order to achieve this group of configurations, the interior surfaces, summing to 352 m^2 FS, were progressively covered, starting from one single scattering sample (16 m^2 FS) and ending with complete coverage. In Table III the details of the 22 configurations are reported, and in Fig. 3 one of them is shown. The criterion for implementing the coverage was to distribute the samples from one surface to an orthogonal one. In some cases, especially when few frames were in place, it was decided to study also setups with scattering patches located on fewer surfaces. The five configurations with concentrated scattering are named with a letter after the number. This made it possible to investigate the scattering performance according to the placement of the samples.

For each of the 22 configurations, 3 source locations, and 20 microphone positions were selected for acoustical measurements, after which the measurement software automatically calculated the T30 parameter according to the regression on the interval [−5 dB; −35 dB] in the octave frequency bands centered from 125 Hz to 1 kHz.

C. Results for the increase of scattering

The first task was to investigate how the condition of diffuseness was reached when the successive setups were analyzed. The core of this part of the work was the investigation into the sound field diffusivity by means of the Davy approach. Like the methods developed by Schroeder[21] and Lubman,[22] this method is based on the spatial variance of the measured quantities (reverberation time, in this case) and can be easily implemented in the practice of room acoustics. The formula used in the comparisons is

$$\frac{\sigma(T)}{T} = \frac{0.96}{\sqrt{BT}}, \qquad (1)$$

where T is the spatially averaged measured reverberation time, σ is its standard deviation, and B is the statistical bandwidth considered. When the left-hand term is smaller than the right-hand term in Eq. (1), that is, the experimental data

TABLE III. Details of the implemented configurations with the respective averaged scattering coefficients derived with respect to the whole interior surface. Setups with the same scattering surface, but with the patches concentrated on fewer surfaces are indicated with a letter after the number.

								Surface averaged scattering coefficient			
Configuration	S scattering total [m^2]	$Sxy1$ [m^2]	$Sxy2$ [m^2]	$Syz1$ [m^2]	$Syz2$ [m^2]	$Szx1$ [m^2]	$Szx2$ [m^2]	125 Hz	250 Hz	500 Hz	1000 Hz
0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1	16	0	0	0	0	16	0	0.00	0.01	0.02	0.03
2	32	0	0	0	16	16	0	0.00	0.02	0.05	0.07
2a	32	0	0	0	32	0	0	0.00	0.02	0.05	0.07
2b	32	0	0	32	0	0	0	0.00	0.02	0.05	0.07
3	48	0	0	0	0	48	0	0.01	0.03	0.07	0.10
4	64	0	32	0	16	16	0	0.01	0.04	0.09	0.14
4a	64	0	0	16	0	32	16	0.01	0.04	0.09	0.14
4b	64	0	0	32	32	0	0	0.01	0.04	0.09	0.14
5	80	0	32	0	16	16	16	0.01	0.05	0.11	0.17
6	96	0	32	16	16	16	16	0.01	0.05	0.14	0.20
7	128	32	32	16	16	16	16	0.02	0.07	0.18	0.27
8	144	32	32	16	16	32	16	0.02	0.08	0.20	0.31
9	160	32	32	16	32	32	16	0.02	0.09	0.23	0.34
10	192	32	64	16	32	32	16	0.03	0.11	0.27	0.41
11	208	32	64	16	32	32	32	0.03	0.12	0.30	0.44
12	224	32	64	32	32	32	32	0.03	0.13	0.32	0.48
13	256	64	64	32	32	32	32	0.04	0.15	0.36	0.55
14	272	64	64	32	32	48	32	0.04	0.15	0.39	0.58
15	304	64	96	32	32	48	32	0.04	0.17	0.43	0.65
16	320	64	96	32	32	48	48	0.05	0.18	0.45	0.68
17	352	96	96	32	32	48	48	0.05	0.20	0.50	0.75

are smaller than the predictions, the sound field conditions can be regarded as diffuse. Otherwise, non-diffuse conditions are prevailing.

To start with, the averaged all pass value of T30 measured in the empty, flat reflecting room was 3.61 ± 0.09 [s] and the corresponding Schroeder frequency was set close to 194 Hz. This meant that in the empty room a modal behavior characterized the lower octave band (125 Hz) and partly the 250 Hz octave band.

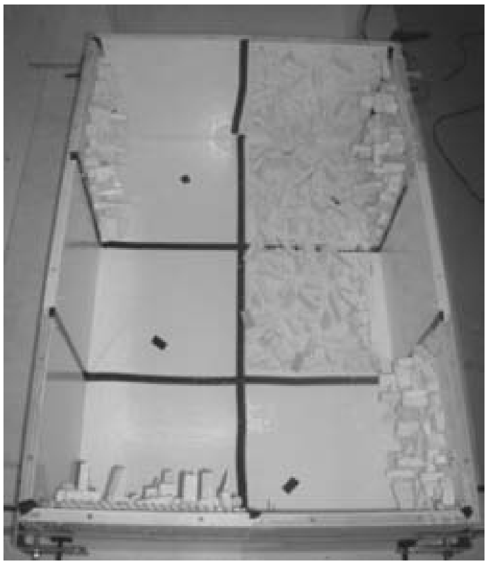

FIG. 3. View of the model room in a configuration with several scattering elements in place (ceiling removed).

Next, the T30 in the 22 configurations were measured and the spatial standard deviations calculated. Results are reported in Fig. 4, where the measured data are plotted with the respective theoretical curves. In the abscissa, one finds the surface averaged scattering coefficient for the given model setup. Those values are obtained in analogy with the averaged sound absorption coefficient and are based on the amount of scattering for the given configuration. In formula

$$\bar{\delta} = \frac{\sum_i S_i S_i}{S_T}, \tag{2}$$

where δ_i is the amount of scattering of the ith area S_i and S_T is the total area.

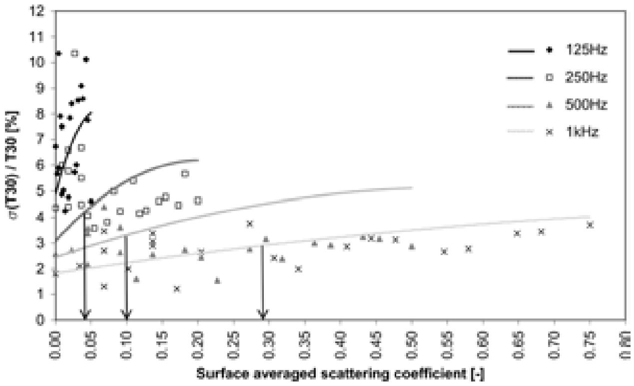

FIG. 4. Statistical deviations derived from Davy's theory: comparison of measured and predicted values. The arrows indicate the scattering values at which the final crossing is found.

As can be seen, except for the 125 Hz octave band which has a quite irregular behavior, the other octave band values cross their respective theoretical curves after passing a few steps in the progression, and all remain below the Davy curves, henceforth. Since the 125 Hz octave band was completely below the Schroeder frequency, where the statistical Davy method is not accurate,[9] this octave was not considered in the rest of the work.

For the higher octaves, and despite some minor variability, the values where the final crossings happened could be extrapolated, and corresponded to the averaged scattering coefficients $\bar{\delta} = 0.04, 0.10, 0.29$ for the 250 Hz, 500 Hz, and 1 kHz, respectively. The first configurations after the crossings are number 5 (80 m^2 of scattering samples) for 250 Hz and 500 Hz, and number 7 (128 m^2) for 1 kHz.

This finding means that the introduction of increasing amounts of scattering surfaces is able to diffuse or "regularize" the sound field, according to the operative definition of the process employed here. Once these values are finally surpassed, the addition of more scattering patches has an impact on the reverberation time due to their intrinsic sound absorption (whose values are reported in Table II), but not on the sound field diffusivity. On the contrary, keeping a scattering lower than the limits indicated above might result in a non-diffuse or "irregular" sound field.

This applies for most of the initial sound fields, with some exceptions. The most interesting example in this respect is the first set of points, which corresponds to the empty room. In this case, there is no scattering patch and the sound absorption is due only to the model varnish. The initial data are above the Davy limit for 250 Hz, slightly above for 500 Hz, and slightly below for 1 kHz. One can see that, due to the limited dimensions, the physical nature of the sound field in the empty room is actually mixed.

Moreover, in Fig. 4 it can also be seen that some configurations share the same average scattering coefficient but show different values in the ordinate axis. Those configurations have the same amount of scattering patches but with a placement more or less concentrated. It is found that the "concentrated" locations tend to be less diffused. In fact the respective points are always above those of the "uniformly distributed" configurations. Thus it is demonstrated that the spreading of the patches maximizes their effectiveness in regularizing the sound field.

Finally, it is curious to note a peculiar behavior in the 1 kHz octave band. This frequency starts with a point below the curve, and then the introduction of one or a few concentrated patches causes slightly non-diffuse conditions. In this specific case, it is believed that the absorption effect of the patches prevails over the scattering one.

D. Using the classical Sabine formula

The next step of the work regarded the prediction of the reverberation time for the whole set of rooms in the progression using the simple classical Sabine formula. This task had the main objective of finding a relationship between the diffuse conditions, the limiting scattering values and the applicability of the Sabine formula.

Starting from the set of acoustical data obtained in Sec. II A, a revision was accomplished in order to have the sound absorption data as immune as possible from edge effects. This was obtained for the scattering patches by operating backward with the Sabine formula on the last model configuration, where all the interior surfaces were covered with scattering patches and only a few free diffracting edges were present.

It was decided to proceed in the same manner for the sound absorption of the interior varnish finishing in the empty room, but this was possible for the 1 kHz band only; in fact, as outlined above, the lower bands in the empty model suffered from not optimal diffusion. Finally, the varnish data were measured in the reverberation chamber for 250 Hz and 500 Hz, whereas the 1 kHz value was derived from the empty scale model. Table II shows the whole set of acoustical properties of the surfaces adopted in the predictions. As can be seen, the edge effect affected specifically the scattering samples so that a remarkable difference was found between measures in the reverberation chamber (RC) and in the scale model room (MR). In fact, the sound absorption depends on the ratio between perimeter and surface (P/S) and for the RC test sample this was equal to unity, so a notable edge effect could be expected. Usually an α_∞ related to an infinite surface can be extrapolated by a regression over a group of measures taken with different sample sizes and then a suitable correction can be calculated for the various block dimensions using the regression coefficient β and the P/S ratio. This procedure is well known when the sound absorption of small samples has to be used for bigger blocks, as in the acoustical design of performance spaces.[23,24]

In the present model setups, the MR values (α_{MR}) could be taken as the diffraction-free reference corresponding approximately to α_∞, but since several free diffracting edges were present, it was necessary to estimate their sound absorption by a procedure derived from Ref. 24. The first task was to evaluate the diffraction effect by calculating the regression coefficient β from the RC measurement, and second, by calculating the width w of the lateral strips to account for it. The following two equations from the literature were used for the scopes:

$$\beta = \frac{\alpha_{RC} - \alpha_{MR}}{P/S}\ [\mathrm{m}], \quad w = \frac{\beta}{\alpha_{MR}}\ [\mathrm{m}]. \tag{3}$$

The output of the procedure was a set of β equal to 0.076 m, 0.092 m, and 0.095 m at 250 Hz, 500 Hz, and 1 kHz, respectively, and widths of the strips equal to 0.80 m, 0.65 m, and 0.55 m FS at the same frequencies. The results are fully compatible with the previous literature and ensured a correct evaluation of the edge effects in the field. Finally, the scattering patches were assigned the α_{MR} values, and lateral strips were added to the free edges when computing the areas prior to applying the Sabine formula. This correction turned out to be a relevant issue in this application and it should not be overlooked in the common practice for medium-smaller rooms. The same effect was better controlled in the case of the measured sound absorption of the audience by using a lateral reflective enclosure as indicated in Ref. 13.

In addition, the border effects related to the so called "Waterhouse effect" were corrected for[9] to include the extra sound absorption for the elements close to the room corners. The whole process was also assessed by considering the small decrease of the available volume (up to 2% for configuration 17) due to the introduction of the scattering samples.

The obtained estimates according to the Sabine formula are sorted by the respective measured values and are reported in Fig. 5. In the abscissa, the averaged scattering coefficients are used to scale the sound fields. The plot includes a line corresponding to unity and the two ±5% lines which can be regarded as the perceptive references corresponding to ±1 just noticeable difference (JND) for T30.[25]

In the empty room (i.e., origin of scattering axis), the values are 0.78, 0.88, and 0.98 for 250 Hz, 500 Hz, and 1 kHz, respectively. Thus, in the absence of scattering patches, the classical formula increases its accuracy with increasing frequency.

Considering the whole progression, one can see that the data sets tend to reach unity as surface average scattering coefficient increases. The 95% border is definitely crossed at the values $\delta = 0.04, 0.10, 0.18$, respectively, for 250 Hz, 500 Hz, 1 kHz. Except for 1 kHz, the point at which the data cross the 95% threshold corresponds to the average scattering coefficient at which the Davy criterion for a diffuse sound field is met. The slight difference at 1 kHz is due to the present choice of the border with a perceptual meaning.

Like Sec. II C, these values can be indicated as those ensuring the usability of the classical formula, provided that a fairly uniform distribution of scattering is accomplished. Using the chosen procedure it was thus possible to establish a relationship between an objective statistical criteria and the simplest diffuse field prediction tool for reverberation. The scattering values were successfully used as parameters and specific reference limits were derived. These points will be further discussed in Sec. IV B .

E. Testing the Nilsson formula

The data set provided an opportunity to test experimentally the analytical formula for the prediction of the reverberation time as developed by Nilsson. In particular, the implementation in the EN norm[1] (Annex D) was used to formulate the reverberation estimate for the progression of setups analyzed in this study. The same input data and corrections as developed in Secs. II A and II D were adopted. The measured scattering values were inserted and no volume scattering was considered, whereas the small reduction of the volume due to the inserted samples was accounted for. To be consistent with the usage of the model, a minimal value of scattering equal to 0.05 was attributed to the flat surfaces.

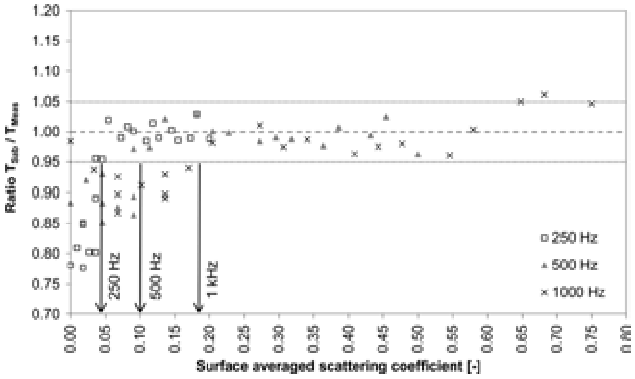

FIG. 5. Ratio of the reverberation times predicted by Sabine with those effectively measured. The ±5% limens are included corresponding to ±1 JND of the parameter. The arrows indicate the scattering values at which the final crossing is found.

The ratio of predicted and measured reverberation times is reported in Fig. 6. The model works better than the classical formula for the first part of the progression, which is in the area where it is supposed to be superior in the description of non-diffuse sound field conditions. Surprisingly, the values do not plateau in the area of ±5%, but have a more irregular course as the sound field conditions begin to be more regular. This is especially true for 500 Hz, but also 250 Hz and partly 1 kHz show deviations. Generally, the formula shows an overestimation in the case of diffuse conditions.

This finding is consistent with previous indications[18] and can give valuable guidance for the best use of the formula. In particular, the design of acoustical treatments often involves the shift from diffuse to non-diffuse conditions (or vice versa); this is what might happen, for instance, when a sound absorbing ceiling is installed in an otherwise flat and reflective room. Thus, care should be taken in using the Nilsson formula in both cases since discrepancies may occur, which probably could be perceived aurally. Furthermore, the overestimation of the reverberation time in the diffuse conditions might cause an overestimation of the amount of acoustical material needed to control the sound tail.

To investigate this finding further, the derivation of the formula was reviewed and the most critical point was found to be the modeling of the grazing absorption, which is based on admittance data. Though a full parametric study was not undertaken here, it was noted that a minimal variation in the modeling parameters might result in a noticeable variability of reverberation. It should also be noted that the nature of the samples was actually not porous, so that the modeling of grazing absorption was, in this case, quite approximate. On the other hand, matching an effective scattering performance with a porous surface finishing would have required solutions too complicated to be easily implemented as frames in the scale model.

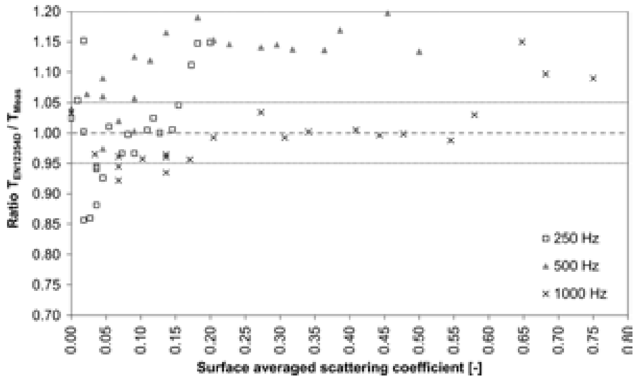

FIG. 6. Ratio of the reverberation times predicted by Nilsson with those effectively measured. The ±5% limens are included as in Fig. 5.

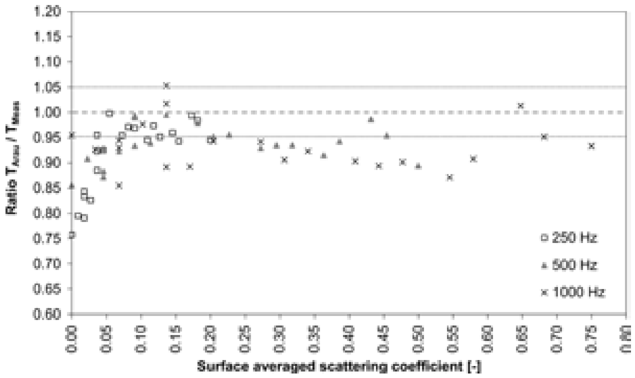

FIG. 7. Ratio of the reverberation times predicted by Arau with those effectively measured. The ±5% limens are included as in Fig. 6.

Finally, a third formula was also employed, which takes into account the different distribution of sound absorption on the three axes but not the scattering. This is the well-known Arau formula.[26] As seen in Fig. 7, the agreement is satisfactory even though the reverberation is generally underestimated when the conditions are more regular, whereas a critical underestimation is found in the first part of the progression. A better match would probably be achieved by using the Eyring coefficients (i.e., obtained by backward operating with the Eyring formula instead of the Sabine one), since the Arau formula is obtained by applying the Eyring formula independently on the three axes.

For a direct comparison of the formulas, the respective absolute averaged deviations from the measured data have been grouped for the sound fields 0–5 (non-diffuse sound fields) and 6–17 (mostly diffuse sound fields) in Table IV. When comparing the frequency averaged values, one sees that in the first group (0–5) the Nilsson formula is nearly twice as accurate as the others. On the contrary, in the group 6–17 the Sabine reaches a remarkable 2% while the Nilsson shows 11%. The Arau has a performance which is close to or slightly worse than Sabine in all cases.

F. Outline of the effect of scattering and absorption

The crucial point in the progression of the sound fields implemented in this study is that the impact of a profiled patch is always twofold in the sense that both scattering and absorption affect the sound field and somehow its diffusivity. The evidence that sound absorption has an impact on the diffusion of the sound field in rooms has long since been established. In particular, the diffusion tends to be reduced if the sound absorption is concentrated on a few surfaces and not uniformly distributed in the space.[9] On the contrary, scattering greatly increases the sound field diffusion and, hence, the two surface properties can be considered as opponents in the process of regularizing the sound field. In practice, when dealing with a single finishing, balancing the two surface properties is at the basis of the sound field characteristics.

In order to explore the interplay of the two surface properties for the present case, the data were further elaborated. In particular, the scattering and absorption units (both in [m^2]) at each progressive setup were normalized with respect to their highest possible values, which are the final $\bar{\alpha}$ and $\bar{\delta}$ multiplied by S_T and represent the total available scattering and absorption units. By doing so, the increasing scattering and absorption data in the progression can be interpreted as "potentials" of absorption/scattering of the samples. Reaching unity will mean having displayed all of the possible impacts on the sound field or, in other words, to have covered the whole available inner surface with the patches. With this idea in mind, in Fig. 8 one can see the joint absorption/scattering data. The plots are separated due to the different starting point for each frequency. The black circles in the plot represent the points of 95% transition described in Fig. 5 for the ratio of Sabine predictions with measured data.

In particular, diffuse conditions are reached in the 250 Hz–1 kHz bands when the samples have displayed just 20%–25% of their scattering potentials, whereas absorption has already been employed for up to 50%. One may argue that diffuse conditions would not be reached at all with a progression of flat sound absorbing samples having negligible scattering. This is actually what was found in Ref. 27. The present data show how, for this type of patch, the diffusing effect of scattering is clearly prevailing over the sound absorption.

As a more general conclusion, one can say that adding some scattering to a sound absorption finishing would be a good strategy to achieve at once the requested reverberation and robust diffuse conditions in the room. Once such conditions are reached, the Sabine formula may also be safely used. The main practical advantage of this approach is to obtain the previous goals with less acoustic material installed. This will be further confirmed below, when discussing the performance of flat absorbing layers in the empty room.

III. APPLICATION TO AN EQUIPPED ROOM

A. Setups

The same scale model was then prepared with a 1:16 scaled audience in order to simulate more realistic conditions and to investigate how the prediction of the reverberation

TABLE IV. Absolute averaged percent deviations of the formulas with respect to the measured data for the setups in the progression. 0–5: 10 non-diffused setups; 6–17: 12 mostly diffused setups. Numbers in parenthesis indicate the standard deviations of the averaged values.

	250 Hz			500 Hz			1 kHz			Avgerage 250 Hz–1 kHz		
Setups	0–5	6–17	0–17	0–5	6–17	0–17	0–5	6–17	0–17	0–5	6–17	0–17
Nilsson	7(6)	13(4)	10(6)	6(4)	16(3)	12(6)	5(1)	4(5)	4(4)	6(2)	11(3)	9(4)
Sabine	15(7)	1(1)	8(8)	10(4)	2(1)	5(5)	8(3)	3(2)	5(4)	11(4)	2(1)	6(5)
Arau	15(7)	3(2)	9(7)	8(5)	5(3)	6(4)	7(4)	8(3)	7(3)	13(4)	5(2)	9(5)

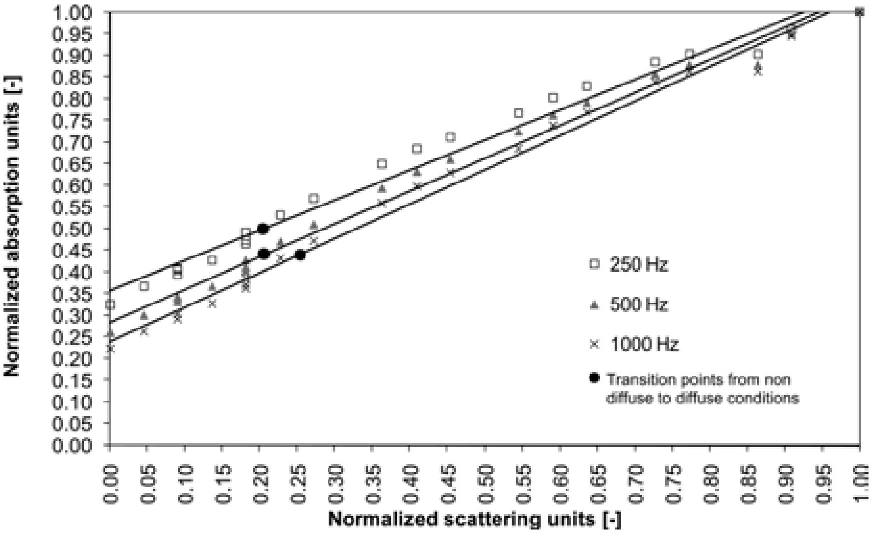

FIG. 8. Outline of the roles of sound absorption and sound scattering in the progression. The sound scattering (x-axis) and sound absorbing (y-axis) units are both normalized with respect to their maximum final value. The regression lines are included for easiness of reading. Black circles in the plot indicate the points at which the sound fields become diffuse as described in Fig. 5.

time can be effective in those cases. Some absorbing and scattering samples were also used and the scheme of the setups is reported in Table V. Eight preparations were selected, named from A to H. The first subgroup (A to D) included the empty room (A) and three setups with one surface only fully covered with a layer of curtain; they are named, respectively, B (whole ceiling covered), C (one long wall covered), and D (one short wall covered). In the setups E to H, the lateral walls are kept reflective and the scaled audience is inserted, while the ceiling is alternately reflective (E), absorbing (F), or scattering (G). Finally, in the H setup, while keeping a sound absorbing ceiling, the lateral walls were prepared as completely scattering.

The choice of the above "occupied" setups is intended to represent a room with a specific acoustic vocation (typically a meeting/conference room, a classroom, or similar). For each room setup, a complete set of acoustical measurements was collected with the same measurement chain as above. Measures regarded at least 3 source positions for 24 receiver positions uniformly distributed in the space.

As before, in this part of the work the set of formulas was employed to make predictions on reverberation time. In fact, despite the rather familiar type of room and setup, the parameter was not always accurately predicted due to an uneven distribution of the surface properties, as has been documented for classrooms.[28–30]

In order to have a more complete comparison, acoustical computer-aided design (CAD) models of the room in the A–G setups were prepared. This task was accomplished with a commercial hybrid tracing program.[31] The software was fed with the same sound absorption data used in the prediction formulas. The sound scattering is required by the program as a single number at a given frequency, and the complete frequency trend is then automatically reconstructed. For this reason the closest possible match with the measured data was sought, and it was obtained by giving as inputs the frequency and the scattering measured in the typical "knee" region, where the parameter shifts from low to higher values.

Moreover other relevant input data were the type of scattering, set to "Lambert" with "reflection based enabled," the transition order, set to 3, and finally the number of rays which was set equal to 3000 except for the empty room, where it was 5000. The number of sound sources and receivers in the simulations were 3 and 24, respectively, and both were distributed uniformly in the room volume.

B. Results for the reverberation time

First of all, the study of these sound fields starts with the calculation of the Davy's ratios from theory and experiment. The results are reported in Table VI. The data are marked in bold characters when the measured data exceed the theoretical data and thus, the sound field can be considered non-diffuse. This is actually what happens in the majority of cases and only condition H shows a distribution of

TABLE V. Details of the configuration of the model described in Sec. II (equipped room). Reflective: plain varnished surface, absorbing: one layer of curtain over the whole surface, scattering: surface fully covered with scattering patches.

Configuration	Audience	Floor *Sxy*1	Ceiling *Sxy*2	Short wall *Syz*1	Short wall *Syz*2	Long wall *Szx*1	Long wall *Szx*2
A	No	Reflective	Reflective	Reflective	Reflective	Reflective	Reflective
B	No	Reflective	Absorbing	Reflective	Reflective	Reflective	Reflective
C	No	Reflective	Reflective	Reflective	Reflective	Absorbing	Reflective
D	No	Reflective	Reflective	Absorbing	Reflective	Reflective	Reflective
E	Yes	Reflective	Reflective	Reflective	Reflective	Reflective	Reflective
F	Yes	Reflective	Absorbing	Reflective	Reflective	Reflective	Reflective
G	Yes	Reflective	Scattering	Reflective	Reflective	Reflective	Reflective
H	Yes	Reflective	Absorbing	Scattering	Scattering	Scattering	Scattering

TABLE VI. Comparison of the theoretical and experimental values according to Davy's theory. Values in bold indicate that the diffuse conditions are not verified.

Configuration	250 Hz Theoretical	250 Hz Measured	500 Hz Theoretical	500 Hz Measured	1 kHz Theoretical	1 kHz Measured
A	**3.1%**	**4.4%**	**2.5%**	**2.6%**	1.9%	1.8%
B	**4.2%**	**9.7%**	**3.3%**	**8.6%**	**2.5%**	**9.0%**
C	**4.5%**	**16.8%**	**3.3%**	**11.9%**	**2.5%**	**9.9%**
D	**6.3%**	**7.6%**	**3.4%**	**4.3%**	**2.3%**	**7.0%**
E	**4.2%**	**4.2%**	**3.3%**	**5.0%**	**2.5%**	**7.1%**
F	**7.3%**	**8.0%**	**5.4%**	**6.3%**	**3.1%**	**5.7%**
G	4.9%	4.7%	4.0%	3.4%	**3.0%**	**3.1%**
H	8.0%	6.8%	7.0%	4.2%	5.4%	4.9%

reverberation time that appears properly diffuse in the whole frequency range. From this, it may be immediately understood why estimating reverberation time in those rooms is often not a straightforward task.

Next, the comparison of the predictions (either formulas or CAD simulations) is done by calculating the absolute averaged percentage discrepancy of each estimate with respect to the measured data. This is done for the relevant octaves as above (250 Hz to 1 kHz) and is reported separately for the two subgroups of setups A–D and E–H in Table VII. With regard to the first group (A–D), it is seen that the Nilsson approach seems to be the most effective (8% when averaged across frequencies), followed by the Arau which shows 17% on average, CAD at 20%, and finally Sabine with a discrepancy as big as 31%.

It is to be remarked that the best CAD results were obtained for the empty room with scattering set to zero, whereas setting the value at 0.05 caused, in this specific case, an underestimation of all the band values because the sound field turned out to be too diffuse. In the other cases, when at least two different finishes were present, such discrepancy was not observed and the scattering in the CAD simulations was kept for the flat surfaces at the minimal suggested value of 0.05.

The results for the second group of sound fields (E–H) can now be analyzed. In these "occupied" conditions it is seen that, except for Sabine, the absolute discrepancies tend to increase with respect to the previous case. In particular, the detailed analysis showed that conditions E and F are underestimated by CAD and the reverse is true for G. Here (scattering ceiling), a better estimate with CAD was obtained by EDT rather than T30. The last configuration H was well predicted by CAD which has always the best performances in the 1 kHz band. In this set of occupied conditions, Nilsson slightly overestimates reverberation time, whereas both Arau and Sabine generally underestimate, except for condition G. When the data are averaged across the bands (250 Hz–1 kHz) the discrepancies are 28% (Sabine), 16% (Nilsson), 21% (Arau), and 28% (CAD).

When compared with results from real classrooms[28] (though with a smaller mean volume and averaged over the 500 Hz–2 kHz frequency bands), the discrepancies are less than halved for Sabine (13.2%) and slightly smaller for CAD (22.9%). On the other hand, in a previous study on simulated classrooms, the respective discrepancies were found as being larger than those found here, that is, always over 30%.[29]

Thus, one can conclude that the benefit of using a CAD model to predict reverberation time in this specific case is fairly limited compared to using simple formulas, since the discrepancies are comparable or wider with respect to the classical or Arau formulas. The approach of the more elaborated Nilsson model has the potential for better depicting actual sound field conditions and provides a more accurate estimate.

IV. DISCUSSION

A. Experimental method

Previous studies have already pointed out that collecting correct surface data in view of the application of the classical formulas is an issue to be investigated.[12] In one study, absorption figures were obtained as in a previous work[32] by inverting the Eyring formula within a large cubic scale model room. Conscientiously, the author explained that this has to be considered as an *a priori* condition in order to formulate estimates according to the classical formulas.

TABLE VII. Absolute averaged percent deviations of the prediction tools with respect to the measured data. The lettering of setups refers to Table V.

Setups	250 Hz ABCD	250 Hz EFGH	250 Hz all	500 Hz ABCD	500 Hz EFGH	500 Hz all	1 kHz ABCD	1 kHz EFGH	1 kHz all	Avgerage 250 Hz–1 kHz ABCD	Avgerage 250 Hz–1 kHz EFGH	Avgerage 250 Hz–1 kHz all
Nilsson	8	16	12	3	24	14	13	9	11	8	16	12
Sabine	22	24	23	36	26	31	35	33	34	31	28	29
Arau	9	21	15	21	16	18	21	25	23	17	21	19
CAD	17	41	29	19	33	26	23	11	17	20	28	24

Unfortunately, in that study, the impact of this statement on the problem could not be firmly assessed.

In the present work, the direct measures of scattering and absorption required particular care and, although experimental accuracy was carefully dealt with, the obtained results were affected by unavoidable errors. This occurrence had to be accepted as part of the normal room-acoustical practice. On the other hand, the impact of such errors on the comparisons was limited, since the prediction formulas were fed with exactly the same figures.

A relevant finding obtained here is the correspondence of the statistical tool proposed by Davy with Sabine's classical formula for reverberation time. These two tools have two different purposes, but showed consistency when applied to the same set of sound fields. The information from the former on the shift to diffuse conditions found a close confirmation from the latter after some known corrections were introduced. This finding can also be seen as a validation of the whole procedure of prediction, since Davy's statistical tools do not rely on the acoustical data of the surfaces and thus on the way those properties are obtained.

In fact, Davy's method only requires reverberation time to be measured and is thus clearly indirect. On the other hand, a direct measurement of diffusion could be difficult (if even practicable) and would strictly depend on the quantity adopted for its definition. Furthermore, the same Davy approach was employed with success a few years ago in the study of diffuse conditions in proportionate rooms.[27]

Moreover, it has to be underlined that this method was used here to assess the diffusion or not of the sound field, but it gave no information on the "quality" or "degree" of diffusion once this condition was finally reached. This latter concept is theoretically investigated in Ref. 8 where, for sound fields with non-grazing waves, a set of indicators can predict the degree of diffusion reached.

Finally, it is to be remarked that the Davy criterion was also included in an International Organization for Standardization (ISO) norm as a means to obtain a working estimate of the measurement uncertainty.[25]

B. Increase of scattering and diffusion

The border values (those at which the final switch to diffuse conditions occurs) increase with frequency, whereas the initial state showed an expected tendency to be more diffused in the higher frequency bands. This evidence is somehow in contrast with the idea that fewer scattering units should suffice in the higher bands to achieve the diffuse state, since they were close to it from the beginning. This apparent paradox was not resolved here and its explanation would require a complete theoretical analysis. The results seem to indicate that for a relatively small amount of material installed, the impact of sound absorption might overwhelm that of the scattering.

One must be cautious in extending border values to rooms with different combinations of volumes and aspect ratios. In particular, if disproportionate rooms are considered (i.e., one dimension much bigger or smaller than the others), it may be harder to achieve diffuse conditions according to the operative definition adopted here, even with diffusely reflecting boundaries. On the contrary, for volumes and aspect ratios not significantly different from the present case, that is, for quasi-cubic shapes, it is believed that the behavior would be quite similar, as the previous experimental results for a bigger room indicate.[27] Thus the results obtained here may help in setting the minimal amount of averaged scattering to be distributed uniformly on the room surfaces in order to ensure diffusion and to adopt simple prediction formulas for the reverberation time.

V. CONCLUSIONS

The regularization of the sound field in a proportionate room of limited volume can be operated by an upper limited amount of scattering elements. The transition from non-diffuse to diffuse conditions was assessed by means of the Davy criterion, which was regarded as a reliable statistical tool to describe the presence of diffuse conditions. The border values correspond to averaged scattering coefficients equal to 0.04 at 250 Hz, 0.10 at 500 Hz, and 0.29 in the 1 kHz band. However, as noted, in the highest band, starting from the value 0.18, the differences in the predictions of reverberation times should be imperceptible.

Averaged scattering values higher than the previous figures are beyond the scope of regularizing the sound field and probably unnecessary if this is the main task. These findings are a first experimental response to the important question of how much scattering is needed in a medium-small size room. This type of room is very common within communities (schools, meeting rooms, etc.). The perceptual relevance of the different amounts of scattering in the same room remains an issue largely to be undertaken in future studies.

Other interesting findings were accomplished especially related to the means of predicting the reverberation time. In particular, the Nilsson model was tested in a systematic way and proved to be within 6%–12% of the measured values in the averaged 250 Hz–1 kHz bands for non-diffuse sound field conditions. This accuracy is acceptable at an engineering level. The other formulas and the acoustical CAD simulations fed with the same data gave larger discrepancies under the same cases. Unfortunately, in more diffused conditions, the Nilsson model has a tendency to overestimate the reverberation time especially in the lower bands. This was not found in a previous computer validation of the model,[17] and is probably an issue to be considered in practical applications.

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