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The effect of scattered reflections on reverberation time in a small non-diffuse room

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ABSTRACT

A series of 700 impulse response measurements of 35 test configurations (including a reference configuration) in a small non-diffuse room were conducted varying the three architectural design characteristics of type, placement, and coverage of diffusing panels to quantify how and with what degree of significance the reverberation times changed among the configurations. The reference configuration was chosen to be the room with no panels installed. The type characteristics was represented using pyramidal and curved panels. Two methods of *"Amount Change"* and statistical hypothesis testing were used for analyzing the measurement data. The analyses of the results showed that even small numbers of diffusing surfaces can markedly affect the reverberation time in a room. As the number of diffusers is increased, the shapes changed from pyramidal to curved, and the design is more distributed, the room will have a more uniform sound field with shorter reverberation times. The changes are greatest in the high frequency bands and smallest in the low frequency bands.

Keywords: Scattered Reflection, Diffusion, Reverberation Time
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1. INTRODUCTION

It has been well documented in the literature, e.g. [1], [2], and [3] that scattered reflections are subjectively desirable in listening spaces, however, quantifying this effect has been elusive to acousticians. These reflections have show to affect the acoustical events of the room both temporally and spatially. For example, these types of surfaces have proven to be effective at preventing echoes in auditoriums and concert halls, as in Carnegie Hall in New York [4], and at reducing coloration in small rooms used for sound reproduction [5]. Another application example is the reduction of focusing effects of concave surfaces, as in a music rehearsal room at the Edwina Palmer Hall in England [3].

While research on the quantification and characterization of the surface scattering is well documented (e.g. two international standards focusing on methods to measure the directional uniformity and deviation from the specular reflections of the surface scattering have been published [6, 7]), fewer studies focus on the effects of these surfaces on the acoustical properties of enclosed spaces. Several of these studies employed scale models and in-situ measurements to determine the effects of diffusing surfaces on the sound field. Jeon *et al.* [8] investigated the effects of wall diffusing elements on the diffuseness of sound-field in both a 1:10 scale model hall and in a real recital hall. Among the results, it was found that diffusive surfaces decreased mainly early decay time (EDT) for both halls. However, other objective acoustical parameters did not show any consistent tendencies with respect to the presence of diffusers. In another work, Jeon *et al.* [2] measured several acoustical parameters, including EDT, reverberation time (T_{30}), and clarity (C_{80}), in two scale models (1:50 and 1:25) of a concert hall. These parameters were measured for different configurations of hemispherical diffusers to examine the ideal zone for diffuser arrangement and investigate the suitable surface coverage and structural height of the diffusers for these ideal zones. It was concluded that half of the side walls closer to the stage were the optimum zone to place the diffusers. Shtrepi *et al.* [9] measured the acoustic scattering effects produced by a lateral diffusive wall in a small variable-acoustics hall. Four objective acoustic parameters were compared between a diffusive and a reflective condition of the wall. It was found that, as the acoustic scattering decreased, the values of EDT and T_{30} decreased while these of C_{80} and definition (D50) increased.

Computer simulations have also been performed to determine the effects of diffusing surfaces on the sound field. Shtrepi *et al.* [10] investigated both objectively and perceptually the effects of different scattering coefficients applied to the walls and ceiling of a simulated concert hall, using three prediction models based on geometrical acoustics. The authors reported that the values of the analyzed acoustic parameters (T_{30}, EDT, C_{80}, and sound strength (G)) depend mainly on the source-to-receiver distance and on the scattering coefficient variation, rather than on the distance from the considered lateral wall. An increase in EDT and a decrease in C_{80} have also been observed for increasing scattering coefficient values for all three software, while no similar trend was observed for the other parameters.

Despite recent advancements in understanding why and where diffusers should be applied, there is a need to further investigate the right placement, amount, or shape of these surfaces as it still seems to be guided by "guess-work" in the design process of rooms [11]. One important difference that causes this research stands out from the previous similar studies is the architectural approach that is implemented in alteration of the characteristics of the diffusing panels in the room. It is considered how an architect might play with their design of the room in regard to using the diffusing panels. As a result, this study intends to be more focused on the effects produced by the inclusion of the diffusing panels on one acoustical parameter, reverberation time, by altering the placement, coverage, and type (shape) of the diffusing panels. Another notable difference is the large number (35) of different measured scattered sound fields or configurations that allowed for a more in-depth analysis of the results and more solid conclusions. Another feature of the present work is the non-diffuse nature of the empty room characterized by a distribution of hard, thus reflective, material on the walls and absorptive materials on the ceiling and floor which allows for a more realistic and practical architectural design scenario.

The remaining sections of this paper are organized as follows. Section 2 describes the impulse response measurement procedure along with the measured room configurations and the two types of diffuser used. Section 3 presents the results of the acoustical parameter measurements. In Section 4, the results are discussed in terms of the significance in parameter differences across room configurations before concluding on the study in Section 5.

2. MEASUREMENT SETUP AND CONFIGURATIONS

2.1. Measurement Setup and Procedure

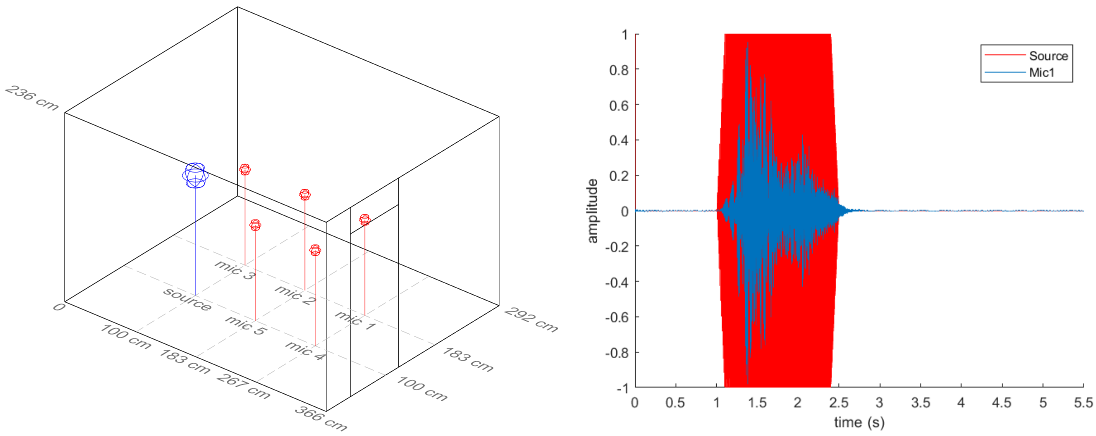
Impulse response measurements were conducted using the method described in [12] in a small unoccupied room of volume V= 25.2 m^2 in a few sessions spread over several days. Since the room was relatively small, the minimum distance requirement between the source, receivers, and boundaries of the room were calculated following the method described in [12] and used in order to include as many receiver locations as possible in the experiment to achieve an appropriate coverage in the room and account for influences likely to cause differences in reverberation time throughout the room. This allowed the experiment to have five evenly distributed locations to be used for the receiver locations. Complying with the method, the height of the receiver (NTi Audio M2230 omni-directional class 1 microphone) and source (Larson Davis BAS001 omni-directional loudspeaker) were chosen to be 120 and 150 cm above the ground, respectively. The source and receivers were located 100 cm away from the surrounding walls and the minimum distance between the source and receivers and between the receivers themselves calculated to be 83 cm using the Equation Equation 1 borrowed from [12] where V is the volume, in cubic meters; c is the speed of sound, in meters per second; and $\widehat{T}$ is an estimate of the expected reverberation time, in seconds.

$$d_{min} = 2\sqrt{\frac{V}{c\widehat{T}}} \quad (1)$$

The output of the signal recorded by the microphone was taken by a signal recorder for calculating the reverberation time. To improve the signal-to-noise ratio, each source-receiver measurement was repeated 4 times for each room configuration, thus resulting in a total of $4 \times 5 = 20$ impulse responses to compute for each room configuration. The room setup including the locations of the source and the receivers and corresponding dimensions in centimeters is shown in Figure 1a using a 3D model of the reference configuration.

The source signal fed to the dodecahedron loudspeaker was a logarithmic sweep of a duration of 4.5 s from 100 Hz to 8 kHz that was generated using a personal laptop. A

100 ms fade-in and fade-out was applied to smooth the amplitude of the excitation signal fed to the loudspeaker. A silence of 3 s was also added in the excitation signal between each sweep repetition to allow for the room response to be fully recorded. Finally, a click was introduced 1 s before the start of the sweep so that the source and recorded signals could be synchronized for the calculation of the impulse response taking into account any delays introduced by the measurement chain (see Figure 1b).



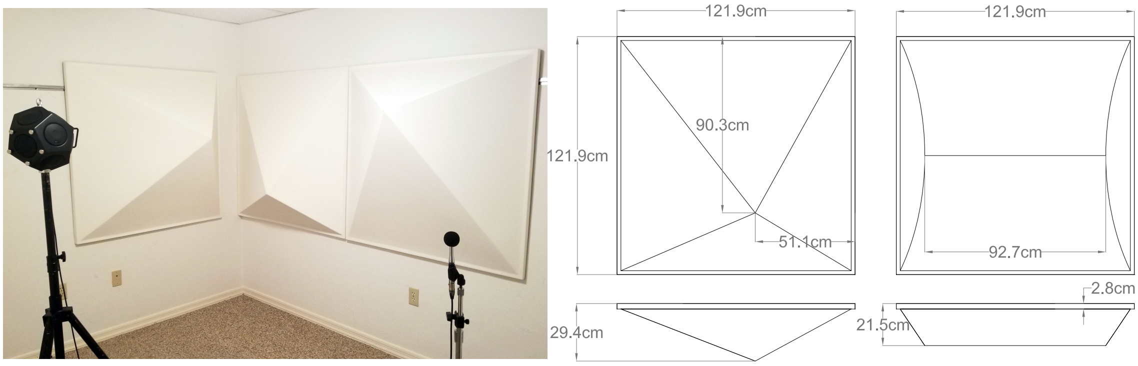
(a) *(b)*

Figure 1: 3D view of the measurement setup in the reference configuration showing the locations of the source and receivers (a). Synchronization of one microphone recording with the source excitation sginal (b).

Impulse responses were calculated after all measurement data were collected from the signals recorded by the moving microphone. First, the microphone recordings were synchronized with the source excitation signal. Using visual inspection, samples corresponding to both the click emitted and recorded were removed from the full source excitation signal and all recorded signals, respectively. After synchronization, recorded signals were convolved with the reversed sweep to result in the impulse response [13].

2.2. Configurations

This study was in fact a part of a bigger study, in which a total of 69 room configurations were tested to explore five architectural design characteristics by analyzing their effects on the room acoustical parameters. These design characteristics were: i. the placement of the diffusers, i.e. the distribution pattern of the diffusers over the wall surfaces; ii. the coverage of the diffusers, i.e. the number of diffusers added in the room; iii. the type of the diffusers, pyramidal or curved shape; iv. the size of the diffusers, either full-size (1.2 m x 1.2 m) or half-size (0.6 m x 0.6 m); v. the combination of different types of diffusers. In the current study, however, the investigation solely focuses on the contribution of the placement, coverage, and type of the diffusers in the change of the room reverberation time, thus reducing the number of configurations to analyze from 69 to 35 (including the reference configuration) and including the configurations with full-size diffusers only. A photo of the measurement setup of one of the configurations (PF3m) and the 2D views and dimensions of the 3D models of the pyramidal and curved diffusers are shown in Figure 2.



(a) *(b)*

Figure 2: Photo of the measurement setup for one of the configurations of study (PF3m) with receiver at location 1 (a). Dimensions and front (top) and top (bottom) 2D views of the pyramidal (left) and curved (right) diffusing panels (b).

3. MEASUREMENT RESULTS

3.1. Grouping the Configurations

A total of six groups were defined for the purpose of the analysis of this study. They are defined in a way that the three design characteristics of the placement, coverage, and type can be analyzed separately. These groups are reported in Table 1 along with the configurations they contain. The 3D views of the configurations are shown in Figure 3. The naming of the configurations corresponds to P: pyramidal diffuser, C: curved diffuser, F: full-size, Integer: number of diffusers in the configuration, and letter: location and pattern of the installation on the walls of the room (arbitrary naming).

Table 1: Groups and their corresponding configurations.

#	Group name	Configurations
1	PF1	PF1a, PF1b, PF1c, PF1d, PF1e
2	PF2	PF2a, PF2f, PF2g, PF2h, PF2i, PF2j
3	PF3	PF3a, PF3k, PF3l, PF3m, PF3n, PF3o
4	CF1	CF1a, CF1b, CF1c, CF1d, CF1e
5	CF2	CF2a, CF2f, CF2g, CF2h, CF2i, CF2j
6	CF3	CF3a, CF3k, CF3l, CF3m, CF3n, CF3o

3.2. Measured Reverberation Times

From the measured impulse responses, the reverberation times were calculated according to the standard [12]. More specifically, the reverberation times were calculated from the decay curves corresponding to the backward integrated squared impulse responses. The investigation of the difference in effects on the reverberation time created at the location of each individual microphone is out of cope of this paper, thus the measurements were averaged across microphone positions resulted in a single value of the reverberation time per configuration per octave band. The calculated reverberation times per octave band for all the 35 configurations of this study are illustrated in Figure 4. The minimum and maximum values of reverberation time for configurations of each

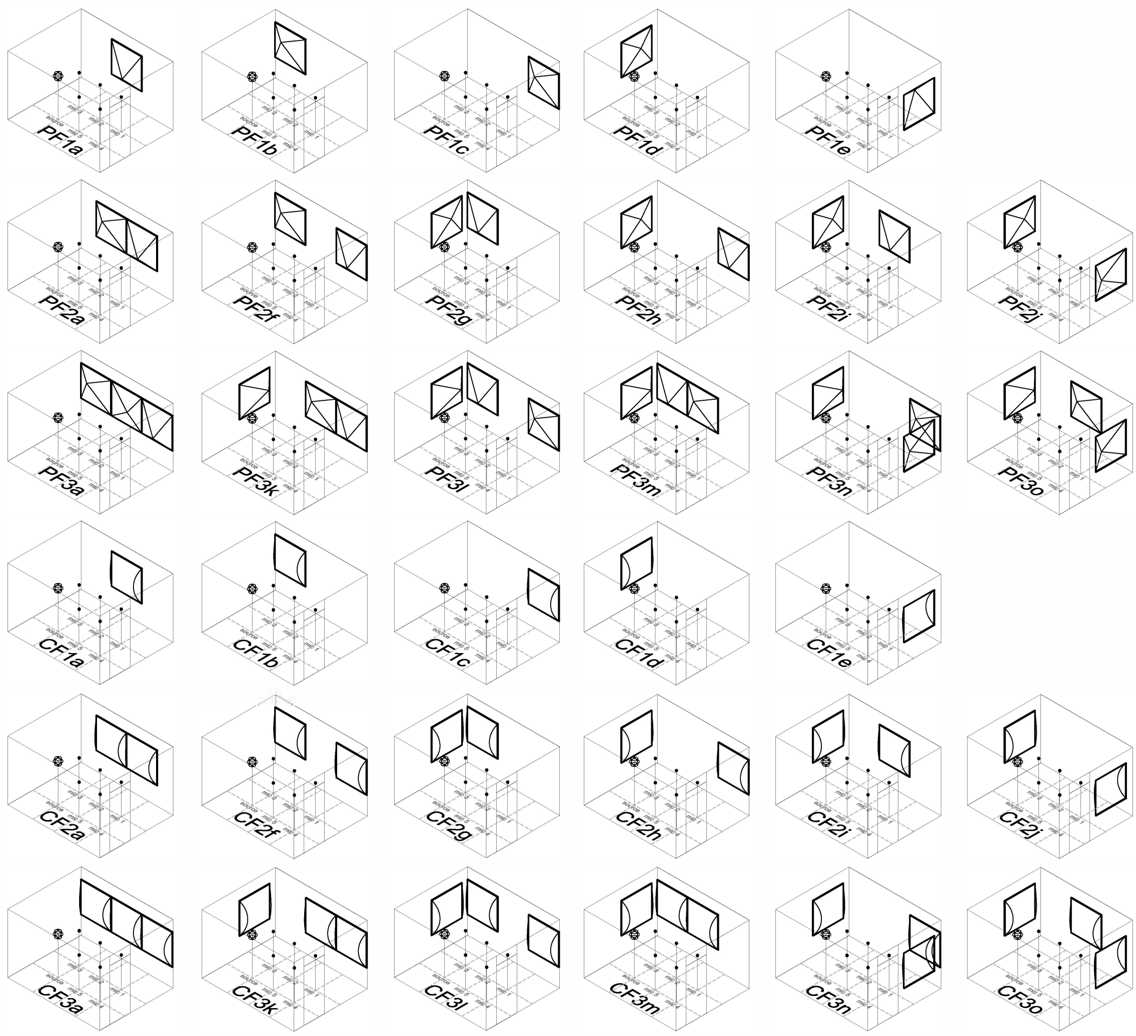


Figure 3: The groups and their corresponding configurations.

group are also reported in Table 2. As it can be seen, the lowest minimum value of T_{30} between the groups occurred in both groups with three pyramidal and three curved diffusers and the highest maximum value of T_{30} took place in the group with one pyramidal diffuser in the low frequency range and the group with one curved diffuser in the mid and high frequency ranges.

4. ANALYSIS OF THE RESULTS

The data was analyzed using two approaches. In the first approach, referred to hereafter as *Amount Change*, the amounts of variation of objective acoustical parameters due to the addition of the diffusers to the empty room are analyzed for the different groups reported in Table 1. In the second approach, a series of statistical tests are carried out to examine the significance of difference in the values of the reverberation time between and within the configurations in Table 1 and the reference configuration. More in-depth statistical analyses are also performed to study the impact factor of the coverage, placement, and type of the diffusers on reverberation time using multivariate regression analysis. As a way of data reduction with the caution of not losing important data, three frequency ranges were defined: a low frequency range comprising center frequencies ranging from

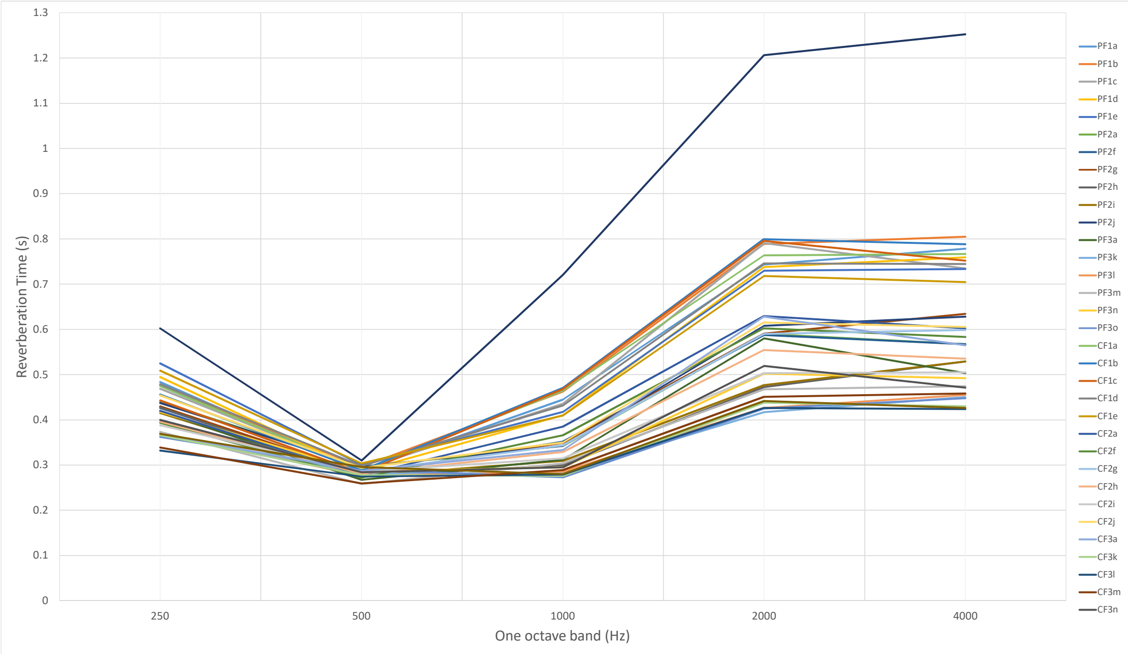


Figure 4: Measured reverberation times for all the 35 configurations in one octave band

*Table 2: The minimum and the maximum values of T_{30} for the configurations of all the six groups of study in the low (L), mid (M), and high (H) frequency ranges. Note that the values in **bold** correspond to the lowest minimum and the highest maximum between the groups.*

	T_{30} Min						T_{30} Max					
	PF1	PF2	PF3	CF1	CF2	CF3	PF1	PF2	PF3	CF1	CF2	CF3
L	0.35	0.3	**0.24**	0.25	0.32	**0.24**	**0.7**	0.59	0.53	0.61	0.53	0.48
M	0.39	0.29	**0.24**	0.38	0.29	**0.24**	0.83	0.69	0.65	**0.91**	0.68	0.67
H	0.6	0.5	**0.4**	0.62	0.49	**0.4**	0.83	0.68	0.54	**0.85**	0.66	0.61

250 Hz to 500 Hz, a mid frequency range including 1 kHz and 2 kHz octave bands, and a high frequency range including the center frequency 4 kHz. For each defined frequency range, the data was averaged across corresponding octave bands, thus resulting in a single value for each of the three defined (low, mid, and high) frequency ranges.

4.1. Assumptions

Two assumptions were made prior to analyzing the data. First, the maximum change in the volume of the room as a result of mounting the diffusers is considered negligible since it is of 2.4% with respect to the reference room. Equation 2 shows the calculation of the maximum change in the room volume (in %) due to the inclusion of three diffusers in the empty room.

$$\frac{\text{volume of 3 diffusers (m}^3\text{)}}{\text{volume of empty room (m}^3\text{)}} = \frac{0.6}{25.2} = 2.4\% \tag{2}$$

Second, the maximum change in the total absorption of the room due to the mounted diffusers is also considered negligible. This assumption is based on the results calculated using Equation 3 and presented in Table 3. As can be seen in Table 3, the maximum change in the total absorption area of the room varies from 0.1% to 5.4% across all octave bands, which can be considered negligible.

$$\text{Percentage change} = 1 - \frac{A_{\text{3diff}}}{A_{\text{ref}}} \tag{3}$$

where A_{3diff} and A_{ref} denote the total absorption of the room containing three diffusers and the empty room, respectively. A_{3diff} and A_{ref} have been calculated using the definition of the absorption given by $A = \sum_i \alpha_i S_i$, where i is the material in the room and α_i and S_i are its absorption coefficient and surface area, respectively.

Table 3: Absorption coefficients of the room surfaces and Pyramid diffuser materials, and the maximum change in the total absorption of the room with respect to the reference room (in %).

Room surface	Area (m^2)	One octave band (Hz)				
		250	500	1000	2000	4000
Pyramid[a]	4.6	0.19	0.14	0.10	0.05	0.08
Ceiling[b]	10.7	0.28	0.38	0.60	0.76	0.77
Floor [3]	10.7	0.08	0.17	0.33	0.59	0.75
Walls [3]	29.4	0.12	0.08	0.06	0.06	0.05
Door [3]	1.7	0.10	0.06	0.08	0.10	0.10
A_{3diff}		7.9	8.6	12.0	16.3	18.0
A_{ref}		7.5	8.3	11.8	16.3	17.9
Percentage change		5.4	4.1	1.9	0.1	1.0

[a] Data adopted from the manufacturer (AVL Systems Co.) data sheet.
[b] Data adopted from the manufacturer (USG) data sheet.

The structure of the wall assembly is comprised of two layers of 13 mm plasterboards on frame with a cavity of 10 cm in between filled with mineral wool. A 80 × 200 cm solid wooden door located on one of the walls discontinues the homogeneous structure of the walls. The floor is covered with loop pile tufted carpet (1.4 kg/m^2) with no underlay, and the ceiling is made of acoustical tiles (USG Radar Ceramic 5/8"). As such, while the wall finishes are made of reflective surfaces, the floor and ceiling are absorptive, resulting in a non-diffuse room. The absorption coefficients of the aforementioned materials are reported in Table 3.

The *Pyramid* and *Convex* diffusers have a volume of 0.17 m^3 and 0.20 m^3, respectively, and rounded up to one decimal their volume is the same (0.20 m^3). Their surface area, as seen from inside the room, is also approximately the same (1.5 m^2 for Pyramid and 1.6 m^2 for Convex). Additionally, both diffuser types are made of the same material. Therefore, their respective absorption coefficients and total absorption area are considered to be the same as well. Consequently, the octave band absorption coefficients of only one type of diffuser (*Pyramid*) are presented in Table 3.

4.2. Amount Change

In this approach, the mean value of the reverberation time (average across microphone positions) measured in each room configuration is subtracted from this of the reference (empty) room. The resulting difference representing the amount of change of reverberation time for the configurations of each group with respect to the reference is expressed in seconds. These amounts of change are shown in Figure 5 per octave band and discussed in the following paragraphs.

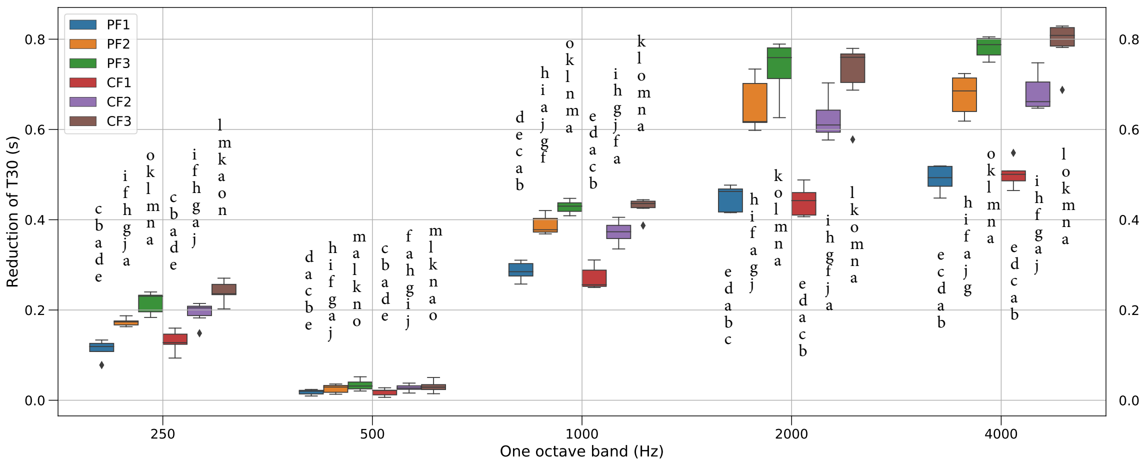


Figure 5: Reduction of T_{30} with respect to the reference configuration per octave band for the configurations of all the groups. Note that the y-axis value of the letters corresponding to the configurations is vertically displaced for better visibility.

From the plot in Figure 5, it can be seen that the change in the reverberation times with respect to the reference in all the configurations resulted in the reduction of T_{30} (No negative value is recorded in the plot).

The amounts of change in the acoustical parameters with respect to the reference were more significant in the mid and high frequency ranges than in the low frequency range. More specifically, the reduction of T_{30} varied from 0.02 to 0.27 s in the low frequency range while it varied from 0.25 to 0.78 s and from 0.45 to 0.83 s in the mid and high frequency ranges, respectively. The minimum reduction of T_{30} occurred in the 500 Hz octave band while the maximum reduction occurred at the center frequency of 4 kHz.

Considering the coverage of the diffusers, the amounts of change were increased as the number of diffusers varied from one to three for all the three frequency ranges. In particular, the reduction of T_{30} reached a minimum of 0.02 s with one diffuser and a maximum of 0.27 s with three diffusers in the low frequency range. The corresponding values for the high frequency range were a minimum of 0.45 a a maximum of 0.83 s. Increasing the number of diffusers from one to two was approximately two times more significant than increasing it from two to three, across the mid and high frequency ranges.

Considering the type of the diffusers, the amounts of change were slightly higher for the curved type compared to the pyramidal type at most of the center frequencies. More specifically, the differences in the amount of reduction of T_{30} between the two diffuser types varied from 0 s in the 500 Hz octave band to 30 ms in the 4 kHz octave band which is insignificant. The differences caused by the type of the diffusers were the greatest for the configurations with three diffusers and the smallest for the configurations with one diffuser.

The study of the effect of the placement of the diffusers on the acoustical parameters can be complex and a comprehensive analysis in this regard is out of scope of this paper. An introductory analysis comparing the two configurations having the maximum and minimum values of the reverberation time in each group (thus only considering the effect of the placement) suggested that the distance between the diffusers and the sound source and the density of the pattern of the installation of the diffusers are two important factors affecting T_{30}. In particular, considering the configurations with one diffuser, those named with the letter e with the greatest distance between the source and the diffuser have the lowest amounts of change in T_{30} in the low frequency range and interestingly the highest amounts of change in the mid and high frequency ranges. For the configurations with three diffusers, configurations named with the letters k, l, and o with a more distributed installation design (lower density) and various distances between the diffusers and the source have the highest amounts of change in the acoustical parameters.

4.3. Statistical Tests

As part of a more comprehensive approach in analyzing the data presented here, four groups of statistical tests named as *Test P, PT, PC, and PTC* are generated to analyze the effects of placement, coverage, and type of the diffusers on T_{30}. The group *Test P* including six tests, analyzes the effect of different placement of the diffusers on T_{30}. The group *Test PT* including three tests, group *Test PC* including two tests, and group *Test PTC* including one test analyze the effect of placement plus type, placement plus coverage, and placement plus type plus coverage of the diffusers on T_{30}, respectively. In each of the four test groups above, three different types of statistical hypothesis tests are carried out in the low, mid, and high frequency ranges resulting in a total of $(6 + 3 + 2 + 1 = 12) \times 3 \times 3 = 108$ hypothesis tests. The types of the hypothesis tests include one-way and two-way ANOVA for comparison test and multivariate regressions for relational test. In the comparison tests, the reference (empty) room is excluded from the analyses. In the regression analyses, however, the reference room is considered as the configuration to be related to.

In this paper for brevity only the tests for the group *Test PTC*, *Test PT* and *Test PC* are presented. Also two-way ANOVA tests which were conducted to analyze the spatial effects of the diffusers on T_{30} are not presented in this paper resulting in a total of $(3 + 2 + 1 = 6) \times 2 \times 3 = 36$ tests. The analyses start with the group *Test PTC*, continue with the group *Test PC* and end with the group *Test PT*.

As it can be seen in Table 4, the one-way ANOVA tests for the group *Test PTC*confirmed that there are significant differences in the value of T_{30} between the six groups of configurations of this study across all the frequency ranges meaning that the combination of changes in the placement, type, and coverage of the diffusers significantly changes the reverberation time. The results of the regression tests showed that any change in the placement, type, and coverage of the diffusers compared to the reference configuration is highly correlated with an R-squared of 0.89 to changes in the value of T_{30} only in the high frequency range.

The analysis of the coefficients in Table 4 showed that the configurations of the group CF3 with three full-size curved diffusers have the most significant effect on T_{30} with the coefficients of 0.27, 0.57, and 0.67 in the low, mid, and high frequency ranges, respectively. The configurations of the group PF1 with one full-size pyramidal diffuser on the other hand, have the least effect on T_{30} with the coefficients of 0.12, 0.37, and 0.4 in the low, mid, and high frequency ranges, respectively. It is also observed that the effects of the combination of changes in the placement, type, and coverage of the diffusers are the greatest in the high frequency range with coefficients ranging from 0.4 to 0.67 and the smallest in the low frequency range with coefficients varying from 0.12 to 0.27.

The results of the one-way ANOVA tests reported in Table 5 for the group *Test PC* showed that there are significant differences in the value of T_{30} between the three groups

Table 4: The results of the one-way ANOVA and multivariate regression tests for the group test PTC in the low, mid, and high frequency ranges.

PF1/PF2/PF3 CF1/CF2/CF3	ANOVA	R-sqr	Intcp.	Coefficients					
Frequency				X1	X2	X3	X4	X5	X6
Low	**1.01E-29**	0.46	0.63	0.12	0.19	0.24	0.15	0.22	0.27
Mid	**9.6E-21**	0.43	0.96	0.37	0.52	0.59	0.36	0.5	0.57
High	**3.06E-99**	**0.89**	1.13	0.4	0.56	0.66	0.42	0.57	0.67
Regr. Eq. (low): T30 = 0.63 - 0.12X1 - 0.19X2 - 0.24X3 - 0.15X4 - 0.22X5 - 0.27X6									
Regr. Eq. (mid): T30 = 0.96 - 0.37X1 - 0.52X2 - 0.59X3 - 0.36X4 - 0.5X5 - 0.57X6									
Regr. Eq. (high): T30 = 1.13 - 0.4X1 - 0.56X2 - 0.66X3 - 0.42X4 - 0.57X5 - 0.67X6									
X1 = PF1, X2 = PF2, X3 = PF3, X4 = CF1, X5 = CF2, X6 = CF3									

of configurations having one, two, and three pyramidal diffusers across all the frequency ranges meaning that changes in the coverage of the pyramidal diffusers from one to three diffusers, significantly change the reverberation time. The results of the regression tests showed that the same changes in the coverage of the pyramidal diffusers compared to the reference configuration is highly correlated with an R-squared of 0.92 to changes in the value of T_{30} only in the high frequency range.

Table 5: The results of the one-way ANOVA and multivariate regression tests for the group test PC for pyramidal diffusers in the low, mid, and high frequency ranges.

PF1/PF2/PF3	ANOVA	R-sqr	Intcp.	Coefficients		
Frequency				X1 (PF1)	X2 (PF2)	X3 (PF3)
Low	**7.47E-14**	0.44	0.63	0.12	0.19	0.24
Mid	**4.97E-12**	0.51	0.96	0.37	0.52	0.59
High	**6.84E-67**	**0.92**	1.13	0.4	0.56	0.66
Regr. Eq. (low): T30 = 0.63 - 0.12X1 - 0.19X2 - 0.24X3						
Regr. Eq. (mid): T30 = 0.96 - 0.37X1 - 0.52X2 - 0.59X3						
Regr. Eq. (high): T30 = 1.13 - 0.4X1 - 0.56X2 - 0.66X3						

The analysis of the coefficients in Table 5 for the group *Test PC* showed that the configurations of the group PF3 with three full-size pyramidal diffusers have the most significant effect on T_{30} with the coefficients of 0.24, 0.59, and 0.66 in the low, mid, and high frequency ranges, respectively. The configurations of the group PF1 with one full-size pyramidal diffuser on the other hand, have the least effect on T_{30} with the coefficients of 0.12, 0.37, and 0.4 in the low, mid, and high frequency ranges, respectively.

Analyzing the effects of the placement plus coverage of the curved diffusers, using the results of the one-way ANOVA tests reported in Table 6 revealed that there are significant differences in the value of T_{30} between the three groups of configurations having one, two, and three curved diffusers across all the frequency ranges meaning that changes in the coverage of the curved diffusers from one to three diffusers, significantly change the reverberation time. The results of the regression tests showed that the same changes in the coverage of the curved diffusers compared to the reference configuration is highly correlated with an R-squared of 0.89 to changes in the value of T_{30} only in the high frequency range.

The analysis of the coefficients in Table 6 showed that the configurations of the group CF3 with three full-size curved diffusers have the most significant effect on T_{30} with the coefficients of 0.27, 0.58, and 0.67 in the low, mid, and high frequency ranges, respectively. The configurations of the group CF1 with one full-size curved diffuser on the other hand, have the least effect on T_{30} with the coefficients of 0.15, 0.36, and 0.42 in the low, mid, and high frequency ranges, respectively.

Table 6: The results of the one-way ANOVA and multivariate regression tests for the group test PC for curved diffusers in the low, mid, and high frequency ranges.

CF1/CF2/CF3	ANOVA	R-sqr	Intcp.	Coefficients		
Frequency				X1 (CF1)	X2 (CF2)	X3 (CF3)
Low	**1.53E-17**	0.57	0.63	0.15	0.22	0.27
Mid	**1.1E-11**	0.49	0.96	0.36	0.5	0.58
High	**1.05E-51**	**0.89**	1.13	0.42	0.57	0.67
Regr. Eq. (low): T30 = 0.63 - 0.15X1 - 0.22X2 - 0.27X3						
Regr. Eq. (mid): T30 = 0.96 - 0.36X1 - 0.5X2 - 0.58X3						
Regr. Eq. (high): T30 = 1.13 - 0.42X1 - 0.57X2 - 0.67X3						

The results of the one-way ANOVA and regression tests for the group *Test PT* which is concerned with the effect of placement plus type of the diffusers are reported in Tables 7, 8, and 9 for one, two, and three diffusers, respectively. The one-way ANOVA tests showed that that there are significant differences in the value of T_{30} between all the two groups of configurations having one, two, or three curved diffuser(s) versus the same number of pyramidal diffusers only in the low frequency range meaning that changes in the type of one, two, or three diffuser(s) from curved shape to the same number of pyramidal shape in each case, significantly change the reverberation time only in the low frequency range.

Table 7: The results of the one-way ANOVA and multivariate regression tests for the group test PT for the configurations with one diffuser in the low, mid, and high frequency ranges.

PF1/CF1	ANOVA	R-sqr	Intcp.	Coefficients	
Frequency				X1 (PF1)	X2 (CF1)
Low	**0.016**	0.25	0.63	0.12	0.15
Mid	0.75	0.26	0.96	0.37	0.35
High	0.11	**0.79**	1.13	0.4	0.42
Regr. Eq. (low): T30 = 0.63 - 0.12X1 - 0.15X2					
Regr. Eq. (mid): T30 = 0.96 - 0.37X1 - 0.35X2					
Regr. Eq. (high): T30 = 1.13 - 0.4X1 - 0.42X2					

The results of the regression tests reported in Tables 7, 8, and 9 for the group *Test PT* showed that the change in the type one, two, and three diffuser(s) from curved shape to pyramidal shape compared to the reference configuration is highly correlated with R-squared values of 0.79 (for one diffuser), 0.89 (for two diffusers), and 0.92 (for three diffusers) to the changes in the value of T_{30} only in the high frequency range.

Table 8: The results of the one-way ANOVA and multivariate regression tests for the group test PT for the configurations with two diffusers in the low, mid, and high frequency ranges.

PF2/CF2	ANOVA	R-sqr	Intcp.	Coefficients	
Frequency				X1 (PF2)	X2 (CF2)
Low	**0.015**	0.42	0.63	0.19	0.22
Mid	0.34	0.49	0.96	0.52	0.5
High	0.14	**0.89**	1.13	0.56	0.57
Regr. Eq. (low): T30 = 0.63 - 0.19X1 - 0.22X2					
Regr. Eq. (mid): T30 = 0.96 - 0.52X1 - 0.5X2					
Regr. Eq. (high): T30 = 1.13 - 0.56X1 - 0.57X2					

Table 9: The results of the one-way ANOVA and multivariate regression tests for the group test PT for the configurations with three diffusers in the low, mid, and high frequency ranges.

PF3/CF3	ANOVA	R-sqr	Intcp.	Coefficients	
Frequency				X1 (PF3)	X2 (CF3)
Low	**0.003**	0.56	0.63	0.24	0.27
Mid	0.455	0.6	0.96	0.59	0.57
High	0.196	**0.92**	1.13	0.66	0.67
Regr. Eq. (low): T30 = 0.63 - 0.24X1 - 0.27X2					
Regr. Eq. (mid): T30 = 0.96 - 0.59X1 - 0.57X2					
Regr. Eq. (high): T30 = 1.13 - 0.66X1 - 0.67X2					

The analysis of the coefficients in Tables 7, 8, and 9 showed that there are not significant differences in the effect of the type of the diffusers on the value of T_{30} in the mid and high frequency ranges with the coefficients varying by at most 6% for curved diffusers being the more effective type. In the low frequency range, however, the effect of the type of the diffusers was most significant for the groups with one diffusers with coefficients varying from 0.12 for pyramidal to 0.15 for curved diffusers. This effect was least significant for the groups with three diffusers with coefficients varying from 0.24 for pyramidal to 0.27 for curved diffusers.

4.4. Discussion

The results and analyses presented in this paper for most part were supporting the findings of the studies presented in the Introduction 1. There were indeed some parts e.g. the comparison between the pyramidal shape and curve shape for which the author could not able to find a similar study to compare or relate to. Those parts added to the specificity of this research. There is also one study [10] [9] conducted by Shtrepi whose results contradicted the finding of this paper by pointing out that increases in reverberation time is observed as a result of a more diffused room. Author believes one explanation for this would be the fact that Shtrepi used ray-based computer programs to simulate the scattered reflections which is questionable considering the fact that rays ignore the phenomena existed as the result of the wave nature of the sound e.g. diffraction effect.

5. CONCLUSIONS AND FUTURE WORKS

Increasing the coverage of the diffusers from 1 to 3 diffusing panels resulted in significant decreases of 0.13 s to 0.66 s in T_{30} with P-values of < 0.001 compared to the reference configuration in the broadband frequencies. Adding 1 to 3 diffusing panels to the reference configuration decreased the T_{30} by average factors - regression coefficients - of 0.13 to 0.67 in the broadband frequencies. As more diffusers were added to the room, the sound energy tended to decay in a shorter time. This occurs because more scattered reflections were created in the room and energy was being decreased per each reflection.

Changing the configurations with 1 to 3 pyramidal diffusers to configurations with the same numbers of curved diffusers resulted in significant decreases of 0.15 s to 0.27 s in T_{30} compared to the reference configuration only in the low frequencies. This means for the configurations and measurement setup of this study the change in the type of the diffusing panels were effective only in low frequencies.

On average, changing the placement of the diffusers from a clustered to a distributed setting, increased the effect factors - regression coefficients - on T_{30} by 0.09 to 0.15 in the broadband frequencies.

In conclusion, even small numbers of diffusing surfaces can markedly affect the reverberation time in a room. As the number of diffusers is increased, the shapes changed from pyramidal to curved, and the design is more distributed, the room will have a more uniform sound field with shorter reverberation times. The changes are greatest in the high frequency bands and smallest in the low frequency bands.

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