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Assessment of reverberation perception in atrium spaces

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Abstract
Atriums, with their large spans and superior voids, in modern life have changed their patterns of use from being only circulation zones to multi-function gathering spaces. This paper aims to investigate the perception and preference of reverberation in atriums of different contexts by their users. The methodology starts with field tests within four atriums of different departments in Bilkent University. As a pilot study, acoustical models of one of the atriums are tuned according to the field tests. Next, interior surface materials are modified for obtaining different sound energy decay rates and auralizations are applied to be used in subjective testing. Lastly, an online questionnaire is held over a sample group. The outcome of this study is to be used in optimizing the acoustical criteria for atriums of different typologies, thus will guide the acoustical design process of such contemporary spaces. Based on the analysis, the groups G2 ($2.05 \leq T30 \leq 2.15$) and G4 ($0.96 \leq T30 \leq 1.29$) are mostly preferred by the participants with the highest scores in the paired comparison tests. Also, a moderate correlation of male participants and their preference in shorter RT is observed. Additionally, the longer T30s are ranked the highest in terms of their appropriateness in this context.

Keywords: Atriums, Reverberation, Preference, Subjective Testing, Room Acoustics.

1 Introduction

As enclosed, daylit, and central spaces, atriums have been used for two thousand years and remain an essential part of modern architecture [1]. They are an inseparable part of building design creating spatial coherence, connecting different spaces and subspaces while bringing social and functional cohesiveness to the whole building. Atriums are a particular form of courtyard from ancient Greek and Roman architecture. By the 19th century and the era of iron and glass, atriums found their new form with longer spans and superior voids, covering the courtyard and social space, controlling climate while benefiting from natural light and sky [2]. The new atriums have become popular and are used at a large variety of building types such as; public buildings, offices, hotels, shopping malls, and leisure spaces. However, the new form of atriums resulted in uncontrolled acoustic factors and longer reverberation [3]. Due to the large volume, unique shape, and the connection of main space to subspaces, the increase of reverberation time in relation to source-receiver distance is suggested to be somewhat more complicated [4]. Hence, causing acoustic discomfort for space's habitants and requires more comprehensive studies [4, 5]. Furthermore, in recent years, designing flexible and multifunctional spaces has become more desirable [5]. Atriums and the activities taking place in them have changed as well; thus, they are no longer only used as circulation spaces but also for social events, gatherings, receptions, exhibitions, or even speeches. As such, the acoustic characteristics of large atriums have become the topic of studies in recent years.

The studies in the field are mainly divided into two main subjects, the subjective and the objective acoustical characteristics of atriums. The studies focusing on subjective perception emphasize on the connection of noise annoyance with Leq variances and reverberation with acoustic comfort [6]. They refer to discomfort due to the continuous reverberation [5] and identify human noise as the dominant factor. The studies use soundscape methodology; sound-walk, measurements, and questionnaires [7] and have been conducted in various enclosed public areas such as hospital and healthcare centers [8, 9], libraries [10, 11], dining spaces [12], and shopping malls [3]. There are also a limited number of studies on preferred listening conditions in sacred places [13, 14]. There have also been studies on the topic of objective acoustic characteristics of atriums, measuring sound pressure level (SPL) and T30 [3, 7] and their relation to the source-receiver distance both vertically and horizontally, suggesting non-diffuse characteristics and non-linear decay curves [4]. Others consider early decay time (EDT) and evaluate the subjective perception of the space, concluding the importance of EDT for communication comfort rather than RT at large atriums [3]. Zhao et al., analyzes the impacts of geometry on T30 and SPL of atriums; the study analyzed and predicted the effects of length, height, l/w ratio, and skylight form and slope on objective parameters using computer simulations [15].

Respectively, the studies have been focusing on both the subjective assessment of soundscape and objective evaluation of atriums acoustics features such as; SPL, STI, RT, and EDT. Nevertheless, the number of studies focusing on atriums' subjective and objective features and the preferential listening conditions is limited. According to Chen and Ma, large interior spaces such as atriums have complex acoustical features resulting in a diverse perception for each individual [16] which necessitates a more comprehensive study of atriums while considering different activity patterns. As such, this study focuses on the subjective perception of reverberation within the context of atrium while evaluating the effects of duration of stay or activities impacting individual's perception to propose an appropriate T30 and EDT criteria regarding the volume and function of these atriums for sustainable use and optimization of acoustical material applications in such spaces. In the scope of this study, initially field tests are held in four different atriums in Bilkent University Department buildings. This study focuses on one of the atriums as a pilot case. The selected atrium is modeled and tuned according to field tests. Auralizations are applied for the present condition of the atrium as well as for various EDT values, which is adjusted by increasing the amount absorption within the atrium. Finally, an online questionnaire is conducted over a sample group of 17 participants, mostly acoustics experts or graduate students, to identify the participants' preference of T30 and EDT in relation to context.

2 Methodology

2.1 Field Measurements

The study is conducted at four atriums of Bilkent University, each being used as multifunctional spaces. The first two atriums belong to the faculty of Fine Art; the atrium of FF building, a four-story height building, which functions as a circulation space, an exhibition, and an open study area on the second floor. The next atrium is FC which many students favor as a study and gathering space. The FC building houses a commercial chain cafe resulting in many students and academicians visiting and spending time at this atrium, particularly during the breaks. The other atrium belongs to the Science faculty and is used as an open study area, seating, circulation, and is additionally used for various events such as the New Year Party. A glass barrel vault covers the atrium with a small fountain in the middle of the atrium. The last atrium is located at the Department of Economics, Administrative, and Social Sciences. Likewise, this atrium with a wide central staircase serves as an open study area, circulation, café, and a platform for final juries and defenses. Table 1 summarizes the primary information of all four atriums, their geometries, typologies, and field-tested mid-frequency reverberation times.

Table 1 - General data of the atriums

Atriums	Name of Faculties	Atrium typology	Volume (m^3)	L × W (m × m)	Heights (m)	T30 (s)
FC	Art, Design, and Architecture	Closed Atrium	3,585	28 × 10	12.8	2.96
FF	Art, Design, and Architecture	Linear Atrium	3,850	30 × 8	16	4.51
SA	Sciences	Linear Atrium	5,450	26 × 10	17.5	3.05
A	Economics, Administrative, and Social Sciences	Closed Atrium	8,482	45 × 13	14.5	2.92

Acoustical measurements were carried out in unoccupied atrium spaces during the winter mid-semester break with minimum background noise. Due to the pandemic conditions, a limited number of students were within the campus; Figure 1 shows photos from each atrium during the field test. According to the ISO 3382-1 [17] standards, the room impulse responses were collected using a dodecahedron Omni-directional sound source set at 1.50 m height, a B&K (Type 2734-A) power amplifier, and the microphone at 1.2 m height. The DIRAC Room Acoustics Software Type 7841 v.4.1 is used to generate e-sweep noise signals. A minimum of 2 sources and 7 receivers' locations (see, Figure 2) is selected for each atrium to collect impulse responses and later to estimate the fundamental acoustical parameter, particularly T30 and EDT, to be utilized in this research. Both parameters are used for tuning the model in later stages. Figure 3 demonstrates the average values of reverberation times (T30) within each atrium.

Figure 1 – Photos from all four atrium spaces in the field tests: a) A, b) FF, c) FC, d) SA atrium

Figure 2 – Sources (S) and receivers (R) locations for each atrium in the field tests: a) A, b) FF, c) FC, d) SA building

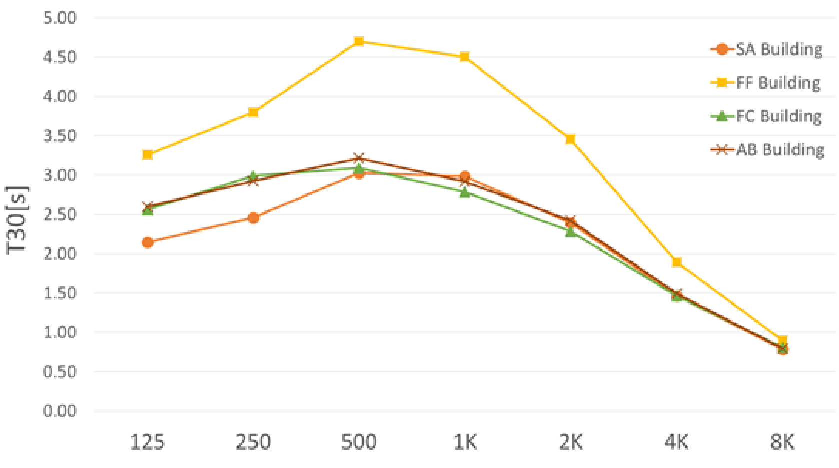

Figure 3 - Average T30 values for SA, FF, FC, and A building's atrium

2.2 Room Acoustics Simulation

For this pilot study, a simplified model of one of the atriums, FC building, is modeled and exported to ODEON Room Acoustics Software version 16. Surface materials are assigned based on site visual observation and standard materials sound absorption coefficients present in the literature, such as ceramic tile flooring, painted concrete, double pane of window glass, etc. Specifically, the paint over concrete and brick surfaces are slightly tuned in reference to measured parameters T30 and EDT for measured source-receiver configurations (Table 2). The difference between simulations and the field measurements for T30 at the same source and receiver position is kept around 0.01s to 0.03s, smaller than the Just Noticeable Difference (JND), making the tuned model adequate.

Table 2 - Material list and sound absorption coefficients over 1/1 octave bands in between 63 Hz to 1000 Hz

Material Location	Name	63	125	250	500	1000
Wall Surfaces	Painted plaster on brick wall	0.09	0.09	0.09	0.09	0.10
Ceiling Surfaces	Painted Conceret	0.01	0.01	0.01	0.01	0.01
Floor Surfaces	Ceramic tiles	0.01	0.01	0.01	0.01	0.02
Coloums	Painted plaster on masonry wall	0.02	0.02	0.02	0.02	0.02
Windows	Ordinary window glass	0.35	0.35	0.25	0.18	0.12
Door	Solid timber door	0.14	0.14	0.10	0.06	0.08
Stair	Ceramic tiles	0.01	0.01	0.01	0.01	0.02
Tables	Wood	0.25	0.25	0.18	0.11	0.08
Painting	Canves covering	0.95	0.90	0.70	0.50	0.35

For auralizations with additions to the measured positions, a total of 25 sources and 4 receivers are located within the atrium in a way to present the typical usage of the atrium; people studying, seating and chatting, cafe employees and customers, and people waiting in the line (See, Figure 4). Next, realistic crowd auralisations are simulated using the multi-source signal auralisation option in ODEON. In the next step to obtain different sound energy decay rates, the absorptive material treatment to ceiling surface is modified by applying a fine finish sound absorptive panel in different percentages of the ceiling area 0% (base condition), 8%, 20%, 35%, 50%, and 100%. Auralization steps are followed for the base/present condition of the atrium and for the adjusted absorption area, as shown in Table 3.

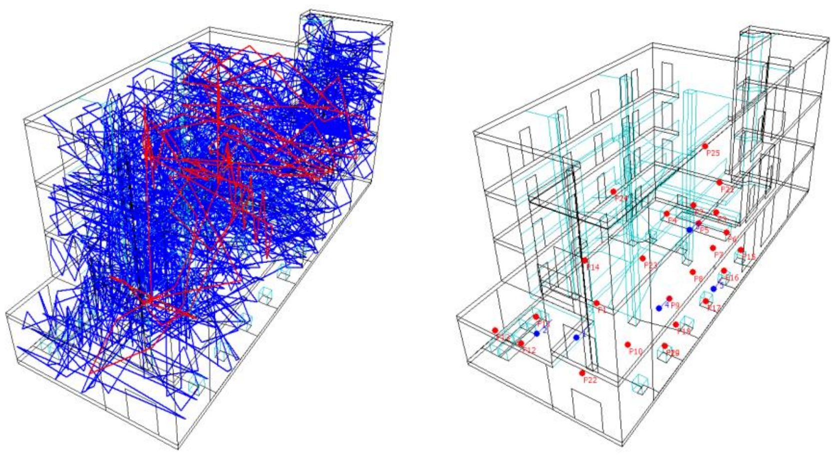

Figure 4 – Ray tracing model and positions of sources and receivers

Table 3 - EDT(s) and T30(s) of eight different source-receiver combinations for different percentage of absorptive material treatment to ceiling surface

Absorptive Material %		R5S17	R5S16	R2S12	R2S17	R3S2	R3S6	R4S9	R4S18
0%	EDT	2.31	2.48	1.44	2.24	2.16	2.13	1.82	2.2
	T30	2.8	2.86	2.87	3.06	2.85	2.8	2.85	2.8
8%	EDT	1.8	1.89	1.02	1.73	1.67	1.57	1.34	1.68
	T30	2.06	2.09	2.12	2.21	2.15	2.07	2.11	2.05
20%	EDT	1.19	1.29	0.71	1.35	1.26	1.11	1	1.27
	T30	1.53	1.59	1.56	1.56	1.65	1.54	1.51	1.54
35%	EDT	0.82	0.91	0.48	1.1	0.96	0.75	0.73	0.99
	T30	1.22	1.28	1.22	1.21	1.29	1.22	1.17	1.19
50%	EDT	0.62	0.78	0.31	0.98	0.79	0.58	0.44	0.85
	T30	1.01	1.15	1.04	1.08	1.07	1.03	0.96	0.97
100%	EDT	0.04	0.31	0.1	0.96	0.52	0.39	0.03	0.62
	T30	0.72	0.75	0.67	0.76	0.99	0.67	0.61	0.64

2.3 Listening Test

2.3.1 Participants

For this pilot study, a total of 17 people, with 82% experienced in the field of acoustics are asked to take the survey. The age of participants varied within the range of 22 to 69 years old. Due to the complication resulted from the pandemic, the subjective experiment is conducted using an online platform where the instructions are given to the participants on how to take the survey. They are enquired to set the level of their headsets/headphones to a comfortable level and are asked not to change it until the end of the survey. After data collection, the participants with inconsistent or inadequate results are screened out for a more reliable evaluation. A summary of participants' general information can be seen in Table 4.

Table 4 – Summary of participants

Profession	Gender	Knowledge of Acoustics	Age
Master/ PhD: 10	Male: 6	YES: 14	> 30 years: 12
Instructor/ Professor: 1	Female: 11	NO: 3	≤ 30 years: 5
Consultant: 3			
Other: 3			

2.3.2 Questionnaire

For the subjective analysis, the audio clips have been classified into five different groups regarding their average reverberation time value (T30), as shown in Table 5. The outliers from each group are eliminated, leaving a total of 43 audio clips to be used for the questionnaire.

Table 5 – Group divisions, their percentage of absorptive material treatment, and T30 (s) range

Groups	Absorptive material %	T30 (s)
G1	0%	2.8 ≤T30≤ 2.87
G2	8%	2.05 ≤T30≤ 2.15
G3	20%	1.51 ≤T30≤ 1.59
G4	35%-50%	0.96 ≤T30≤ 1.29
G5	100%	0.61 ≤T30≤ 0.76

The survey method involves three sections: In the first section, which is a personal survey, the participants are asked about their gender, age, profession, and whether they have any hearing loss. The main purpose of this section is to assess the correlation between participant's preference and their personal characteristics. For section two, the paired comparisons, the survey uses 43 audio clips. This section consists of ten questions comparing pairs of auralisation corresponding to the mentioned five different groups. Pairs are randomly selected from 43 options, ensuring that audio clips from every group (1-5) are compared to each other, and each group is presented as an option four times in a random order to increase the accuracy of the results. Questions are once again randomly presented to participants to enable comparison of stimuli A and B to indicate which recordings the participants prefer. To prevent participants from choosing aimlessly and being forced to pick between A and B, they are also given a third option stating "stimuli A and B sound similar" if they are unable to identify any differences. The last section of the survey is also composed of ten questions, including two audio clips from each group in random order, and participants are asked to assess the appropriateness (authenticity and/or naturalness) of the surrounding sound environment to the present context (the educational atrium). The scale follows the five-point ordinal-category scale of ISO/TS 12913-2:2018 soundscape standards [18], providing the participants with options of "not at all", "slightly", "moderately", "very", and "perfectly". The background picture for each audio clip is assigned corresponding to the actual location in the atrium. The overall listening test is estimated to take around 20 minutes to complete.

3 Results

Due to the small sample size (below 30), the non-parametric Spearman correlation test is conducted in the statistical analysis of the gathered data. For the Spearman correlation test, if the associated significance is less than 0.05, the hypothesis must be rejected. In the case of significance, the correlation coefficient, which ranges from –1 to +1, is analysed. When the value of the correlation coefficient gets closer to 1, it demonstrates a stronger correlation.

First, the obtained results of the selection frequency of the participants are presented together with the primary statistical analysis. According to the distribution of the frequencies of participants selecting one stimuli within pairs as illustrated in Figure 5, when audio clips from groups G2 (2.05 ≤T30≤ 2.15) is paired with G3 (1.51 ≤T30≤ 1.59) and G5 (0.61 ≤T30≤ 0.76) is paired with G1 (2.8 ≤T30≤ 2.87), the participants have the highest rate of recognizing the different pairs. In comparison, the minor recognition takes place when the group; G1 (2.8 ≤T30≤ 2.87) is paired with G2 (2.05 ≤T30≤ 2.15), where nearly 50% of the participants are unable to differentiate the stimuli from one another (see, Figure 5)in this case the EDT of each group respectively is 2.2s and 1.8s.

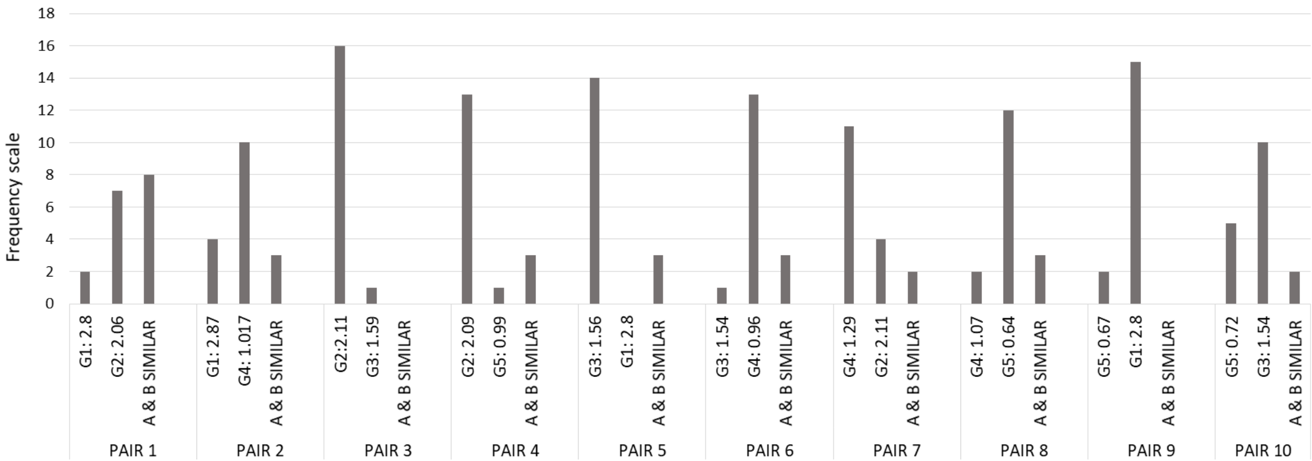

Figure 5 – Frequency distribution: number of times each stimuli is selected by the partcipants.

The primary aim of the section 2 of the subjective perception questionnaire is to assess the participants' preference in relation to RT and the correlation of personal information on their preference. As such after each paired comparison, the preferred stimuli received a +1 score, whereas the other not selected stimuli are given a score of -1. In cases where participants could not differentiate between the pairs, both stimuli are given a score of 0 [14]. For obtaining an overall score and rank of each group, the scores are summed, and the results of each listening test are presented in a garph of preference matrix indicating how many times each group (with different T30 ranges) is preferred by participants (see, Fig 6). The ranking of each group varies between +4 and -4. Based on the matrix results, the T30 group G2 ($2.05 \leq T30 \leq 2.15$) and G4 ($0.96 \leq T30 \leq 1.29$) are mostly preferred by the participants with the highest scores. The group G2 receives the highest range of prefered reverberance, that is when audios from G2 is presented to the particpants as one of the pairs, it is selected as the prefered option except when paired with audios from G4.

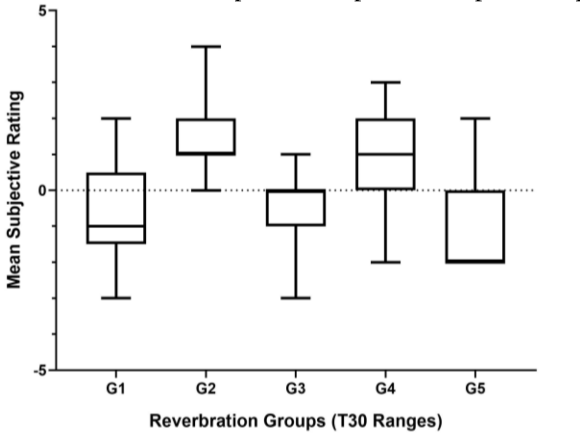

Figure 6 – Average subjective prefernce for the five T30 groups (doted line demonstraets the zero value)

Lastly, by means of Spearman's non-parametric correlation test, the preference of participants in relation to their personal information, provided in the first part of the survey, is analyzed. Considering the limited number of participants, it is found that the preference of RT is independent of the age of the participants and their profession. The analysis also shows a moderate correlation at 0.01 level between the male participants and their tendency to prefer stimuli from G4 ($0.96 \leq T30 \leq 1.29$) with a correlation coefficient of 0.632 and Sig. value of 0.007.

Grounded on ISO/TS 12913-3:2018 soundscape standards for the five-point ordinal-category scale of the questionnaire, scale values of 1,2,3,4, and 5 are assigned respectively for "not at all", "slightly", "moderately", "very", and "perfectly". Using the numeric scale, the total score of each group's appropriateness (authenticity and/or naturalness) per participant is calculated. The graph of the preference matrix of the summed scores is presented in Fig 7. Accordingly, it is found that the longer the reverberation time (respectively audios from G1 and G2), the more they are chosen as the most appropriate according to the presented surrounding by the participants. Therefore, based on section 3 of the survey, when each audio clip is presented and rated as an individual, T30 values between 2.05s and 2.87s are mostly preferred by the participants. In addition, based on the wide distribution range of G1, G3, and G4 scores (from 1 to 4), it can be concluded that the rating of appropriateness is less inconsistency when compared to G2 (from 2 to 4) and G5 (from 1.5 to 3.5). The shortest T30 values, between 0.61 and 1.29, belonging to G4 and G5, have the lowest rating scores and are least preferred by the participants.

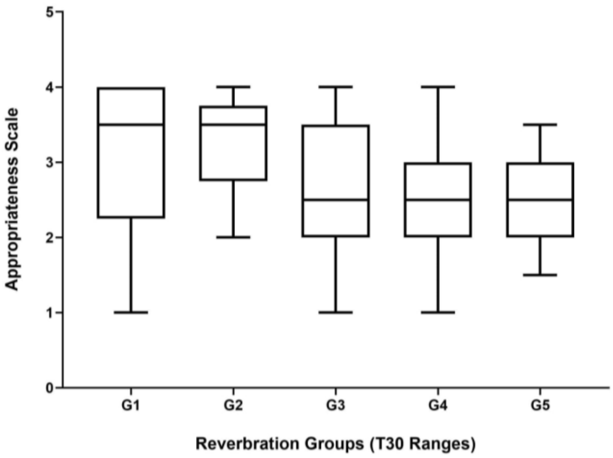

Figure 7 – Average appropiateness of the stimulus for the five T30 groups.

4 Conclusions

In this research's scope, field tests are initially held at four educational atriums of Bilkent University. The field test results indicate that RT values in different atriums range between 2.92s to 4.51s at mid frequencies. For this pilot study, the FC atrium with a T30 of 2.96s is investigated. Listening tests based on paired comparison and five-point ordinal scaling have been employed to assess the subjective preference of reverberation in this pilot multifunctional atrium. The statistical analysis revealed that the participants' preference is independent of the age and profession of the participants, and moderate dependence on male participants and their preference in T30 between 0.96s and 1.29s is observed. Based on the paired comparison, it can be concluded that the recognition of different stimuli is greatest when comparing groups with significant T30 differences like G1 in comparison to G5. However, the participants are also able to identify the different audio clips with T30 of 1.55s and 2.10s but not when the pairs T30 are 2.10s and 2.85s. According to the third part of the survey, the longer T30s are ranked the highest in terms of their appropriateness in this context. Moreover, according to both paired comparison and five-point ordinal scale part of the survey, T30s ranging from 2.05s to 2.15s (G2) with an 8% acoustical treatment application on ceilings is mainly preferred and rated highest as the most appropriate by the participants.

As a pilot study, the limited number of participants (below 30 sample size) and the sample being skewed towards a young female population below 30 years old may have affected the overall results. In the larger scope of this on-going research, the survey will be held over a higher number of real users of the field-tested four atriums. The Auralizations will be held in the rest of the three atriums, as well. The participants will be divided into groups and presented with different surveys with the same pairs but different ordering for more accurate results. Moreover, to better analyse the impacts of EDT on the subjective preference, the grouping of the audio clips will be done based on their EDT, instead of T30 as used in this survey. Additionally, questionnaires will be applied to students to support the listening tests and to understand better the acoustical comfort in reference to different T30 and EDTs in different atriums.

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