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Investigating the Effects of Coupling Factor on Sound Energy Decays of Coupled Volumes

Zühre SÜ GÜL[1]; Gülnihan ATAY[1]; Rozhin NAEEMAEE[1]; Timuçin Berk ATALAY[2]; Hüseyin HACIHABİBOĞLU[2]

[1]Bilkent University, Department of Architecture, Turkey

[2] Middle East Technical University, Graduate School of Informatics, Turkey

ABSTRACT

The decay of sound energy in coupled-volume room configurations can be non-exponential under specific conditions. When designed appropriately, such configurations may offer increased clarity and better spaciousness that are desired qualities, especially for performance venues. While statistically grounded methods can be used to assess non-exponential decay characteristics, architectural aspects of such systems that result in desired audible attributes have yet to be systematically studied. As such, the design of such spaces remains an exploratory pursuit as it has since the first reverberation chambers were attempted in the 1960's. Turning point and level difference obtained from energy decay curves (EDC) can be used to quantify the acoustics of coupled volumes. This study aims to identify the effects of absorption area difference between two rooms on the strength of acoustical coupling empirically assessed through the level difference attribute. For this experimental study, acoustical simulations of two different scenarios of coupled room systems are tested for three fixed aperture sizes and a large number of absorption area. The absorption area is systematically changed by varying the surface materials to gather a set of coupling factors between 0 to 1. The data obtained from ray-tracing simulations are then analyzed via Bayesian decay parameter estimations. Results are comparatively assessed for estimating the correlation between coupling factor versus level differences. In the last step, a listening test is held by using the audio clips obtained from auralizations to assess the audibility and detectability of different levels of double decays.

Keywords: Coupled volume, coupling factor, level difference, multi-slope sound energy decay

1. INTRODUCTION

Non-linear multi exponential decay curves of coupled volumes have always attracted the acousticians' interest. One reason for this attention is that the particular decay has found applications in concert hall acoustics as a design aid. Eugene McDermott Concert Hall in Dallas, TX; KKL Luzern Concert Hall in Switzerland and Birmingham Symphony Hall in London are some well-known examples (1). Not limited to the symphonic music halls, coupled volumes in the form of reverberation chambers are also applied in multi-purpose auditoriums for providing variable acoustical conditions such as in Heydar Aliyev Center Auditorium in Baku, Azerbaijan (2). A very recent and unique example is McPherson Recital Room of Laidlaw Music Center in Scotland (3). Tuning the halls for desired early and late sound energy decays necessitates a thorough understanding of the underlying phenomena or long-term practical experience.

Coupled rooms, can also be observed in many different forms within different building typologies. Some examples are atrium spaces coupled to corridors and corridors coupled to office spaces. Such daily real-case coupled volume examples are critical in auralization studies and even more compelling in real-time virtual acoustics and virtual reality applications (4-7). Theoretical studies on acoustically coupled rooms aim to identify and characterize the decay patterns. Major recently applied approaches are based on wave theory (8), ray-based geometrical acoustics (8), diffusion equation model (10-14) and surface coupling approach (15). On the other hand, the quantification of acoustical

[1] zuhre@bilkent.edu.tr

coupling has always been a challenge. Methodologies applying statistical inference are found to be more appropriate in scientific discussion (16-18) on coupled room acoustics, rather than some arbitrary divisions of energy decay for defining ratios to gather coupling quantifiers or visual interpretation.

This study investigates an intermediate research question of the applied science: To what extent the architectural parameters affect the audibility of the degree or strength of acoustical coupling Particularly, the level difference being the quantifier for the acoustical coupling defined within the Bayesian framework (16,17) is compared with the coupling factor (19), which is a measure embedding the architectural parameters within its input variables. Decay level difference (ΔL) is an important quantifier that indicates the actual strength of coupling that this study focuses on. For a double-decay system, the decay level difference is the difference between the levels of individual decay terms (in dB), extracted from the EDC. One of the objectives is to find a correlation between architectural and acoustical parameters that portray a space. The following objective, is to use this data in systematic investigation of the audibility and detectability of different levels of double slopes, through listening tests. Perceptibility and subjective assessment of non-exponential energy decay have also previously been studied by some researchers (20-23) for specific cases. This study aims to further expand the current state of information, by a systematic investigation on the changes on coupling factor and level difference. The methodology of this study and the major outcomes are presented in the following chapters.

2. METHODOLOGY

In this study a systematic analysis of two different scenarios of coupled rooms is carried out in order to compare sound energy decay parameters obtained via Bayesian analysis to architectural parameters through the coupling factor (Eq. 1). The statistical theory on energy decay in coupled volumes specifies the energy exchange between rooms by the *coupling factor*; a parameter that takes into consideration of the absorption areas of two rooms and the surface area of coupling aperture (24). Billon et al. (19), defines the *mean coupling factor* as follows;

$$k = \sqrt{k_S k_R} = \sqrt{\frac{S_C^2}{(S_C + A_R)\times(S_C + A_S)}} \tag{1}$$

where A_S *and* A_R are the absorption areas of the two rooms, S_c is the area of coupling aperture. $k \approx 1$ denotes strong coupling, meaning that the two rooms behave as a single larger one and $k \approx 0$ indicates a weak coupling, or no coupling, indicating weak energy transfer from the source room to the receiving room. The identification of the conditions under which the energy transfer results in a double (or multiple) slope sound energy decay is one of the research questions that this study looks into.

As already published in recent literature (16, 17), Bayesian decay parameter estimation applies model selection based on the Bayesian information criterion on real or simulated room impulse responses. Schroeder decay functions, obtained through Schroeder backward integration are compared with the parametric model to first detect the number of slopes and then to characterize the decay rates and decay levels. Bayesian model-based parameter estimation selects the most parsimonious multi-rate model that fits the decay curve and can be summarized in Eq. 2 as follows;

$$H_S(A,T,t_i) = A_0(t_K - t_i) + \sum_{j=1}^{S} A_j\left(e^{\frac{-13.8\times t_i}{T_j}} - e^{\frac{-13.8\times t_K}{T_j}}\right) \tag{2}$$

where index $0 \le i \le K-1$. The decay parameters $\{A_j: A_1, A_2, \ldots, A_S\}$ are the amplitude parameters associated with the individual exponential decay terms when expressed logarithmically, T_j is the decay time associated with the logarithmic decay slopes of individual exponential decay terms, with j = 1, 2, …, S where S is the number of exponential decay terms, also termed decay orders. $A_0(t_K - t_i)$ is a noise term and t_K is the upper limit of Schroeder integration, where the subscript K is the total number of data points and t_i with a lower-case subscript i represents the discrete time variable (i.e. *sample index*) (17).

In this study, two configurations of coupled volume rooms are generated via computer simulations.

The first scenario is a two-room coupled system that does not necessarily replicate a real-case, as the aim is to produce different coupling factors by varying the absorption area of one room, whereas keeping the large room constant and with the highest reverberation. This room set-up has previously been tested using a 1:8 scale model for various aperture sizes (25). The computer-generated acoustic model is fine-tuned in a recent study to test an artificial reverberator method based on scattering delay networks (SDN) (26). In these two studies the model is fixed to specific absorption area ratios of the two rooms, while the aperture size is systematically changed. The two aperture ratios of %15 and %30 of the common wall, respectively, are selected for this study, as these two aperture sizes produced similar results in all scale-model tests, coupled volume SDN (CV-SDN) and ray-tracing models (26). Keeping the aperture and the absorption area of the large room constant, the absorption coefficients of surface materials for the small room are increased from 0,01 to 0,9 stepwise. The absorption coefficient for all surfaces for the large room has always been kept constant at 0,01. ODEON Room Acoustics Software version 17.03 is used in ray-tracing simulations. An omnidirectional point source and an omnidirectional receiver are placed at positions corresponding to the same positions as in the measurements. Identical absorption coefficients are assigned to all octave bands in order to get a flat response in broadband, and the analyses are held only for 1 kHz.

The second scenario in terms of room configuration is a typical corridor to open-office coupling condition when the door is open. With a totally different layout, the aim is to achieve similar coupling factors as obtained in scenario 1 by varying the absorption area of the small room (office). Similarly, the absorption coefficients of surface materials for the small room from are changed from 0,01 to 0,8 stepwise, while the sound absorption coefficients of surface materials are kept constant in the corridor at 0,01 for all octave bands. Note that 0,01 as a sound absorption coefficient is very typical for painted masonry, brick or concrete walls and ceiling slabs; as well as for stone (marble, ceramic) surfaces. Table 1 lists the geometric features of room configurations for scenario 1 and 2. Table 2 lists the obtained coupling factors when the absorption area has systematically changed for the small room. Resulting T30 values for the decoupled conditions of the rooms are also indicated in Table 2. Fig. 1 shows the ray-tracing models of scenario 1 and 2 respectively. The room impulse responses are collected for each step of absorption change and the scenario given in Table 2. Later, the RIRs are analyzed using Bayesian decay parameter estimation.

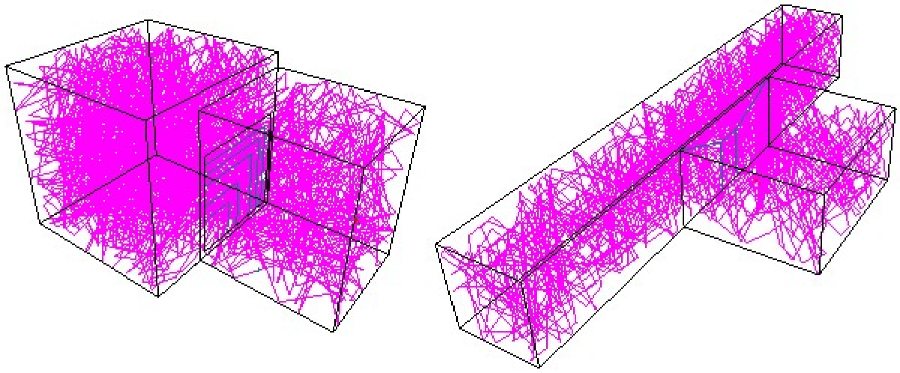

Figure 1 – Ray tracing models of scenario 1; small-large room coupling (on the left) and scenario 2; office-corridor coupling (on the right)

Table 1 – Geometric features of two-room coupled configurations, scenarios 1 and 2

Scenario 1	Small Room	Large Room
Dimensions (m)	4,8 x 5,6 x 6,4	7,2 x 6,8 x 7
Volume (m^3)	172	343
Aperture area – %15 of common partition (m^2)	4,6	
Aperture area – %30 of common partition (m^2)	9,2	
Scenario 2	Room	Corridor
Dimensions (m)	5 x 6 x 3	3 x 20 x 3
Volume (m^3)	90	180
Aperture area - %11 of common partition (m^2)	2	

Table 2 – Coupling factors for different absorption coefficients and T30 values for de-coupled rooms, scenario 1 and 2

Scenario 1				
Alpha (small room)	T30 (s) for 1 kHz (small room)	T30 (s) for 1 kHz (large room)	Mean coupling factor (*k*) %15 aperture	Mean coupling factor (*k*) %30 aperture
0,01	11	13	0,66	0,79
0,03	4,8	13	0,52	0,68
0,05	3,05	13	0,45	0,61
0,1	1,57	13	0,35	0,50
0,2	0,77	13	0,26	0,39
0,3	0,50	13	0,21	0,33
0,4	0,35	13	0,19	0,29
0,5	0,27	13	0,17	0,26
0,6	0,21	13	0,15	0,24
0,7	0,17	13	0,14	0,22
0,8	0,14	13	0,13	0,21
0,9	0,11	13	0,13	0,20
Scenario 2				
Alpha (office)	T30 (s) for 1 kHz (office)	T30 (s) for 1 kHz (corridor)	Mean coupling factor (*k*) %11 aperture(door)	
0,01	7,97	7,42	0,52	
0,02	4,59	7,42	0,44	
0,03	3,25	7,42	0,39	
0,05	2,07	7,42	0,32	
0,1	1,09	7,42	0,24	
0,2	0,54	7,42	0,18	
0,3	0,35	7,42	0,15	
0,4	0,25	7,42	0,13	
0,5	0,19	7,42	0,12	
0,6	0,14	7,42	0,11	
0,7	0,11	7,42	0,10	
0,8	0,09	7,42	0,09	

In the final phase, a pilot study is carried out in order to assess the perceptual aspects of multiple slope energy decay. The simulated RIRs are convolved with a speech signal and audio clips obtained through auralizations are used as stimuli in a subjective listening experiment with 19 participants. The testing is conducted via an online platform. The audio clips are grouped under four clusters in accordance with the calculated level differences (ΔL) (Table 3). Pairings are randomly drawn from a list containing a total of 22 audio clips. Each pair is selected from the aforementioned four groups. Two types of pairings of single and double decays as well as double decay comparisons are used in subjective testing. The participants are asked to compare the perceived reverberance of the paired audio clips and comment on the more reverberant case. They are also asked whether any of the stimuli has a double slope energy decay. The pairs selected from different groups are repeated two times in random order so as to observe if there is any correlation between the subjective responses and the level differences. Results are discussed in the following section.

Table 3 – Audio clips collected under four groups based on the level differences and mean coupling factors

Group A ($2 \leq \Delta L < 5$)			**Group B ($5 \leq \Delta L < 8$)**			**Group C ($8 \leq \Delta L < 11$)**			**Group D ($11 \leq \Delta L < 14$)**		
$0.33 \leq k \leq 0.45$			$0.22 \leq k \leq 0.32$			$0.18 \leq k \leq 0.21$			$0.12 \leq k \leq 0.15$		
#	k	ΔL(dB)	#	k	ΔL(dB)	#	k	ΔL(dB)	#	k	ΔL(dB)
1	0.45	2.5	1	0.26	6.2	1	0.21	9.5	1	0.15	12
2	0.35	4	2	0.29	5.5	2	0.19	10.5	2	0.14	12.5
3	0.39	2.5	3	0.26	6.5	3	0.21	8.5	3	0.13	12.5
4	0.33	4	4	0.24	7.5	4	0.18	9.5	4	0.13	11.5
5	0.44	2.5	5	0.22	7.5				5	0.12	11.5
6	0.39	3.5	6	0.32	5.5						
			7	0.24	7.5						

3. RESULTS

In this section initially the Bayesian decay parameter results are presented for all the tested scenarios and absorption ratios. Table 4 presents the first decay rate (T1), second decay rate (T2) and corresponding levels where the decays start. In addition to that a correlation between the level difference and mean coupling factor is searched. According to Table 4 it can be stated that over 0,50 mean coupling factor the sound energy decay is observed to be a single slope case for the assessed scenarios. And, as the coupling factor drops till around 0,10 – 0,15, ΔL increases. The rate of increase drops as the coupling factor decreases (Fig. 2).

Table 4 – Decay parameter results; (T1, T2, A1, A2), level difference (ΔL) versus mean coupling factor (*k*) for different steps of absorption for the assessed scenarios

Aperture	*k*	# of slopes	T1 (s)	T2 (s)	A1 (dB)	A2 (dB)	ΔL(dB)
15%	0,66	1	12,5				
15%	0,52	1	9				
15%	0,45	2	2	7,8	-6,5	-9	2,5
15%	0,35	2	1,3	6,3	-7	-11	4
15%	0,26	2	0,8	5	-7	-13,2	6,2
15%	0,21	2	0,5	4,5	-6,5	-16	9,5
15%	0,19	2	0,4	3,9	-6,5	-17	10,5
15%	0,17	2	0,3	3,4	-6,5	-18	11,5
15%	0,15	2	0,29	3	-6,5	-18,5	12
15%	0,14	2	0,23	2,6	-6,5	-19	12,5
15%	0,13	2	0,21	2,23	-6,5	-19	12,5
30%	0,79	1	13				
30%	0,68	1	9				
30%	0,61	1	7				
30%	0,5	1	5				
30%	0,39	2	0,55	4	-6,5	-9	2,5
30%	0,33	2	0,55	3,6	-6,5	-10,5	4
30%	0,29	2	0,4	3,2	-6,5	-12	5,5
30%	0,26	2	0,35	2,9	-6,5	-13	6,5
30%	0,24	2	0,31	2,6	-6,5	-14	7,5
30%	0,22	2	0,25	2,3	-6,5	-14	7,5
30%	0,21	2	0,2	2,2	-6,5	-15	8,5
11%	0,52	1	7,6				
11%	0,44	2	2,8	6,4	-6,5	-9	2,5
11%	0,39	2	2,7	5,6	-6,5	-10	3,5
11%	0,32	2	2,1	4,8	-6,5	-12	5,5
11%	0,24	2	1,2	3,8	-6,5	-14	7,5
11%	0,18	2	0,6	2,7	-6,5	-16	9,5
11%	0,15	2	0,3	2,2	-6,5	-17	10,5
11%	0,13	2	0,2	2	-6,5	-18	11,5
11%	0,12	2	0,18	1,8	-6,5	-18	11,5

This pattern of *k* versus ΔL is similar for all the coupling aperture ratios for the tested scenarios. In order to better visualize Bayesian decay parameter results a sample double slope case is presented in Figure 3. This impulse response is for the first scenario, %15 aperture opening and when the small room has an 0,6-absorption coefficient attained to all its surfaces. For this specific case *k* is 0,15 and *ΔL* is 12 dB.

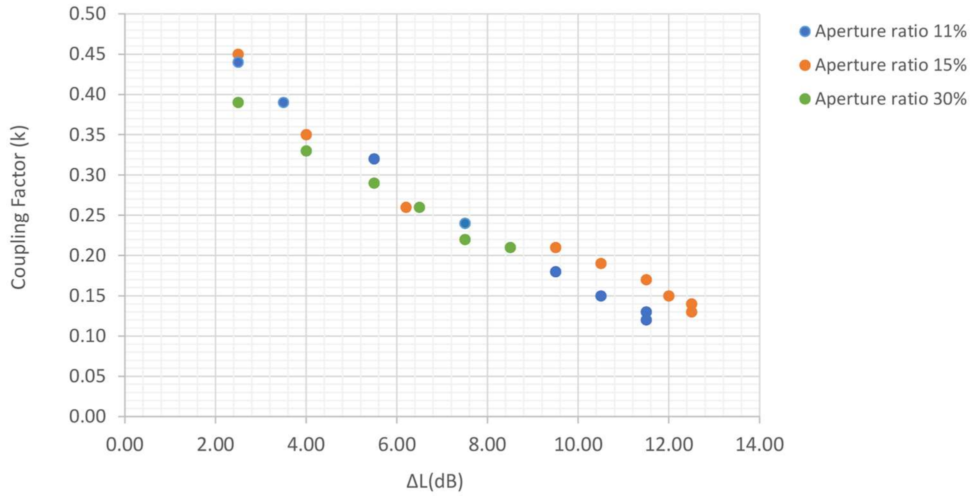

Figure 2 – The correlation between mean coupling factor and level difference for assessed RIRs

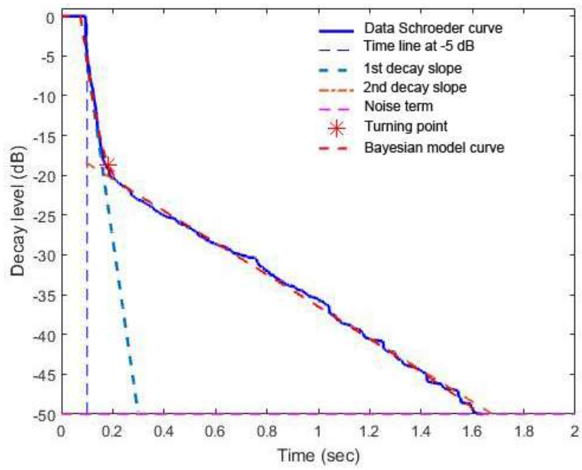

Figure 3 – Schroeder curve and the model curve derived from RIR gathered from ray-tracing simulations for %15 aperture opening, 0,1 alpha step for small room, scenario 1, filtered for 1 kHz.

Figure 4. demonstrates the results of the final phase investigating the perceptual aspects of multiple slope energy decay. The Question A of the listening tests asks for the more reverberant audio clip in paired comparisons. The Question B asks for the clip that is more likely to have double slope. This second question also aims to assess the audibility or detectability of the strength of coupling in comparison to the coupling factors and level differences. In single slope double slope comparison pairs, the sample with T2 closer to the T60 of single slope cases are selected. In the Question A of the listening tests, the single slope cases are found to be perceived more reverberant. This may be due to the fact that in double decay - single decay comparisons T1 is much smaller when compared to T60 of the single slope case. This may suggest the dominance of the early decay component in reverberation perception. When the T1 of single decay rate clips and T2 of the other clip are close in both pairs, the participants have hard time to differentiate the pairs. The single decay audio clips with longer T1 are selected as the most reverberant regardless of the T2 value of the double decay audio clip. In the Question B of the listening tests, the participants have difficulties differentiating single decay rates from double decay rates. The higher the difference between coupling factors, the easier it is for participants to select the audio clip with double decay rates. When the coupling factors of

the pairs are close, the answers are distributed evenly. When the ratio of the coupling factors of the pairs are minimum of two, participants find it simpler to distinguish the pair with the higher coupling factor.

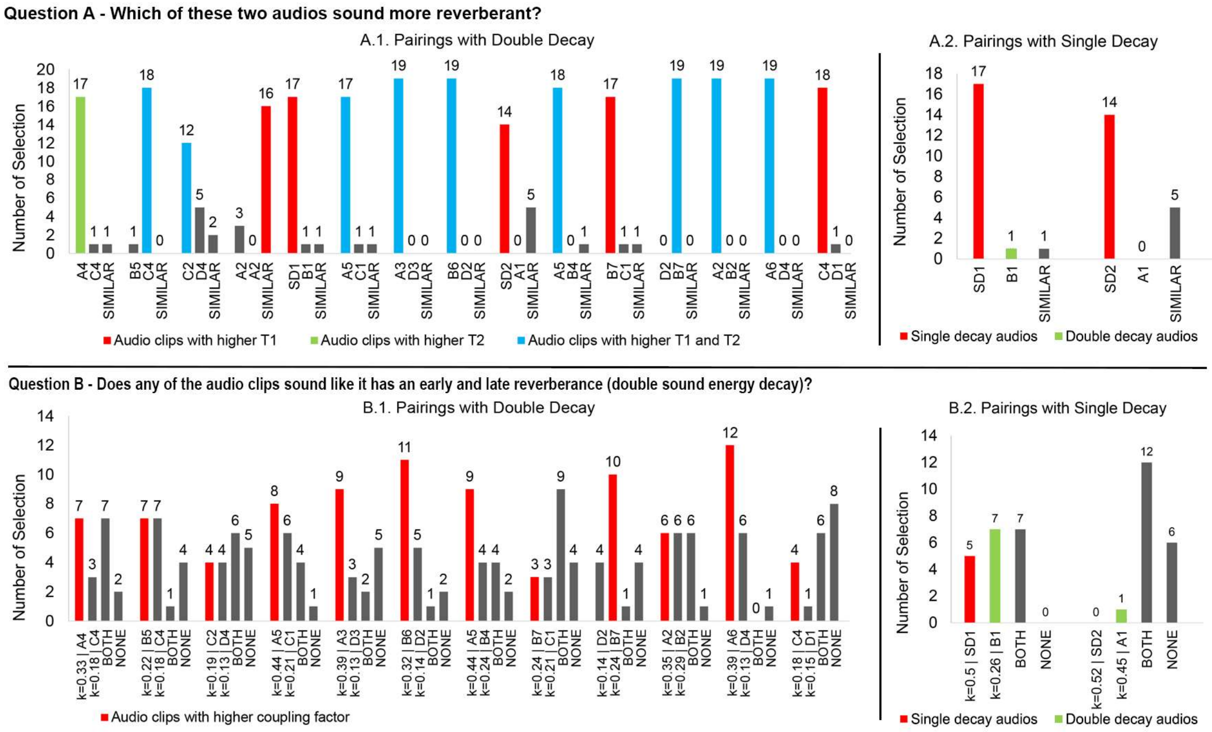

Figure 4. Listening test results of audio clips obtained for paired comparisons of different double decay slopes with varying level differences (on the left) and paired comparisons of single decay versus double decay rates (on the right)

4. CONCLUSION

This study investigates systematically the relation between architectural (absorption area, aperture size) and acoustical parameters (ΔL, T1, T2) in formation of multi-slope sound energy decay. Accordingly, inverse proportion has been found in between the mean coupling factor and level difference (ΔL). Higher the coupling factor lower is the ΔL. On the other hand, the samples with ΔL higher than 0,50 demonstrates a single slope decay in assessed scenarios. In the next step the audibility of the strength of double decay is searched by a pilot listening test. Main outcomes of this test are that the first decay (T1) of a double slope case is more dominant in the reverberation perception and higher the difference between the coupling factors it is easier to differentiate between different pairs. As a future work of this study, the perception and preference of the multi-slope sound energy decays will be assessed in greater detail with a larger sample group of comparisons that will also include convolved music clips.

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