DOI: 10.61782/fa.2023.0235

PERCEPTION OF REVERBERATION LENGTH IN ROOMS WITH ACTIVE ACOUSTICS ENHANCEMENT SYSTEMS

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ABSTRACT

This study investigates the subjective perception of reverberation length in rooms equipped with Active Acoustic Enhancement Systems (AAES) under the condition of laboratory listening test. While numerous acousticians have investigated the correlation between subjective judgment of reverberation and objective criteria in concert halls, the impact of AAES on these evaluations has not been thoroughly explored. The decay of acoustic energy in rooms with AAES has a double-slope characteristic, which distinguishes it from most impulse responses recorded in rooms without this system. The study reveals a difference in the evaluation of the perceived length of "stop-chord" and "running" reverberation. Results also suggest that not only the initial part but also the later part of the impulse response (IR) should be considered in the evaluation of the reverberation length perception. These findings contribute to a better understanding of the relationship between subjective perception and objective measures of reverberation length and provide insights into the perceptual evaluation of acoustic environments.

Keywords: *room acoustics, reverberation perception, active acoustics*

1. INTRODUCTION

Reverberation time (RT), first defined by W. C. Sabine remains the basic parameter for evaluating interior acoustics [1]. While additional parameters have also been defined, RT remains the primary parameter, often being the only one reported. Many room acoustics parameters are based on energy decay and correlate with RT, with some, such as Bass Ratio or Treble Ratio directly derived from RT [2]. The correlation between subjective judgment of reverberation and objective criteria has been extensively studied. Atal and Schroeder [3] pointed to the first 160 ms of the IR as the most important for the perception of reverberation. Jordan [4] proposed the Early Decay Time (EDT) as the measure of the first 10 dB of the decay, which in his opinion best correlates with the sense of reverberation length. In 1974 Hungarian acousticians [5] used 24 audio sample pairs in the test conducted with 25 listeners in an anechoic chamber and 136 listeners with headphone test. The researchers did not obtain conclusive results and pointed out the complex process of reverberation perception and the need for further research to better understand it. Kahle and Jullien [6] suggested expanding the effective duration of EDT time window and utilizing the 15 dB decay as the optimal indicator of reverberation time based on their empirical investigations and auditory assessments of several European auditoriums. The study by Soulodre and Bradley found higher correlation of EDT than RT20 with subjectively perceived reverberation in laboratory tests with anechoic musical excerpts convolved with concert hall IRs and presented to listeners under laboratory conditions [7]. It should be noted that most of the experiments were conducted with a small group of a few or a dozen listeners. Barron [8] widely investigated 17 British concert halls. The author focused on the relationship between EDT and RT, the variability of the

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distribution of values and the influence of hall architecture on this relationship. He does not relate the objective measure of RT to the subjective evaluation on reverberation length, taking the results of the previous studies as valid, but points out to new directions in research on the perception of reverberation. The author asks if current measurement techniques is adequate for subjective assessment, what is the impact of EDT at low frequencies on reverberation perception and whether perception is affected by the magnitude of diffusion of acoustic field.

Nowadays, the need to provide different acoustic solutions for events of different nature have led to the construction of halls with variable acoustic conditions. Altering the size or geometry of an enclosure and implementing suitable acoustic treatments can potentially enhance its acoustic characteristics. However, the effectiveness of these modifications is frequently restricted and inadequate due to practical limitations and technical restrictions. Therefore, active acoustic enhancement systems (AAES) based on signal processing and multi-source redistribution of the modified signal in the room are becoming increasingly popular. The use of such systems makes it possible to adjust the acoustic parameters required for a given performance. The earliest application of the AAES containing microphone-speaker loops which were merely to generate additional resonances and reflections were introduced in the 1960s [9,10]. Generally, active enhancement of the acoustic behavior of the room can be achieved in two different ways: either by adding reflection based on the room's natural reflection (regenerative approach) or by synthesizing reflection based on the direct sound (in-line approach). Regenerative systems use omnidirectional microphones placed over the critical distance from the sound source, regenerating natural reflections within the loops containing microphone, delay line, amplifier and speaker. In contrast, in-line systems use cardioid microphones placed relatively close to the sound source and artificial reverberation engines in each system's loop, adding artificial reverberation to original sound captured by the microphones [11,12]. Over the years, several systems have been proposed by different manufacturers. Most recent AAESs are hybrid systems with both - regenerative and in-line sections which provide a stable, natural sounding diffuse reverberation field [13]. It must be emphasized that most of the reverberations generated by the AAES have non-linear IR slopes which distinguish them from most IRs recorded in concert halls without this system. Regenerative part of AAES regenerate the natural reverberation od the room and in consequence it affects more strongly the late part of energy than the early part of the energy. In-line part of AAES uses artificial reverberation in addition to natural reverberation of the hall, however due to desire to preserve the natural sound of the hall the artificial reverberation should not be generated before natural reflections are generated in the room which also results in a stronger impact on the later part of acoustical energy. As the consequence, the early part of the energy is not increased as much as the last part of the energy resulting in a double-slope IR shape. It is clearly visible in differences in EDT and RT values (for linear decay they should approximately be the same). For example: mean value of EDT-RT ratio for IRs gathered in halls with AAES used in this experiment is 0,61 with standard deviation of 0,13 while mean measured EDT-RT ratio for 17 British concert halls described in [8] was 0,91 with a standard deviation of 0,12. Double-slope IR characteristics obtained from AAES are therefore similar to the IRs shape obtained from the rooms with coupled chambers. Indeed, the way some of the AAESs work is based on the acoustic coupling of the hall with the virtual chamber of AAES [14]. One of the claimed advantages of coupled systems is that they can maintain clarity with late reverberation by the deliberate use of double-sloped decays [15]. Similar to mentioned above, Barron also pointed out the case where, for a low EDT-RT ratio, it is possible to simultaneously achieve high intimacy and adequate reverberation time [8].

Furthermore, according to ISO 3382 [16] standard, due to the difficulty of achieving a 60 dB drop during measurements, RT20 and RT30 parameters were introduced for 20 and 30 dB (measured beginning from -5 dB below stable state) level decays, respectively. Additionally, RT10, as 10 dB drop can be considered as an intermediate measure between EDT and RT20. As it was mentioned above, for IRs with a perfect linear fading shape, the EDT, RT 10, RT20 and RT30 values are equal to each other; however, in reality, IRs with perfectly linear decay are not encountered. Finally, considering the reverberation perception, the Just Noticeable Difference (JND) for EDT and RT was found to be approximately 5% based on research [17], however more recent research [18] indicates rather the ETD JND value of 18%.

The discussion on standards regarding objective measurements and interpreting results is still ongoing [19] and further studies will undoubtedly bring change to existing parameters, however in this study we refer to currently used standards. Adopting such a methodology would enable the comparison of the findings of the current investigation with those obtained from analogous experiments conducted previously.

2. AIM

The objective of this experiment was to determine the optimal objective measure - EDT, RT10, RT20, or RT30 - that correlates with the subjective sense of reverberation length perceived by listeners, in the presence of reverberation generated by the AAES, and to assess if this perception is consistent in rooms with and without the AAES. In addition, the study sought to investigate whether the perception of reverberation length is affected when IRs have a double-slope shape, thus addressing a partially unresolved question in this domain.

3. MATERIALS AND METHODS

This experiment investigates the perceived reverberation length for reverbs generated by AAES. A listening test was conducted to assess the effect of a single parameter (EDT, RT10, RT20, RT30) on the perceived reverberation length. The test involved presenting pairs of stereo sound samples that differed only in one of the mentioned above objective parameter values used to quantify the reverberation length, and the listeners were asked to compare the samples and indicate which one they perceived to have a longer reverberation length.

1.1. Impulse Responses (IRs)

Considering the spatial characteristics of reverberation, stereophonic audio samples were deemed appropriate for the experiment to faithfully recreate the conditions in the concert hall. AKG 414C B-ULS microphones in Mid-Side (M-S) configuration consisting of a cardioid microphone and a figure-of-eight microphone were used to capture over 200 IRs from five different concert halls equipped with AAES. Of the five rooms in which IR recordings were conducted, four are multi-purpose halls with an AAES installed and one hall is a room with AAES installed for demonstration purposes. All the halls have auditoriums of similar size ranging from 320 to 408 spectators. All the halls were built or renovated with the intention of installing an AAES.

Further measurements were conducted in three concert halls that had varying lengths of reverberation time to verify that the results obtained for EDT, RT10, RT20, and RT30 using the M-S system were consistent with the results obtained using omnidirectional microphones. The average values for both systems fell within the standard deviation of each other for every measured octave, indicating that the use of the M-S system did not compromise the accuracy of the obtained results. The values of the all parameters shown in the study were averaged from measurement bands from 125 Hz to 8 kHz for each measurement point. The EASERA Pro v. 1.2 software was used to collect IRs and to calculate parameters values. EASERA Pro v. 1.2 calculate values of the parameters as extrapolated from level fall-off specific for the individual parameter, which is in accordance with the requirements of measurement standard [16].

1.2. Stimuli

The IRs used to generate the audio samples for the listening test were selected such that the values of the three of four (EDT, RT10, RT20, RT30) parameters were in close proximity to each other, i.e., the difference between the parameter values was less than half of the JND threshold for that particular parameter and the value of the parameter being investigated was selected such that the difference between the values was at least one and a half times the JND for that parameter.

To align with the latest research in this field, the experiment included two modes of reverberation: “running” and “stop-chord”. As shown in previous studies, the late part of IRs is associated with reverberation length perception for “stop-chord” while the EDT is more associated with the sense of reverberation length for “running reverberation” [20]. Moreover, Lokki [21] obtained two distinctly different assessments of reverberation length depending on the musical excerpt used during the test and suggested that one measure (EDT) cannot predict the difference between “running” and “stop-chord” reverberances.

The anechoic recordings used in this experiment were brief instrument excerpts, ranging from 15 seconds to 20 seconds in duration. These excerpts included a solo flugelhorn playing a melody to represent "running" reverberation, as well as even beats on the snare drum to represent "stop-chord" reverberation. These anechoic recordings were convolved with the IRs to create the stimuli for the listening test.

For the snare drum sound samples, the listeners were able to perceive both the buildup and decay of the reverberation. Conversely, for the flugelhorn sound samples, the beginning and end of the sound samples were gradually faded in and out to ensure that the listeners could not perceive the buildup and decay of the reverberation. The melody played on the flugelhorn was continuous, with no pauses.

1.2.1. IRs with different EDT

Table 1 displays the values of the objective parameters for the sound samples used in the experiment that aimed to investigate the impact of changing the EDT value on the perception of reverberation length. The difference in EDT values between the samples is greater than 0,15 s and the difference between the values of the other parameters, that is RT10, RT20 and RT30 is less than 0,03 s.

Table 1: Measured values for different EDT

pair/ sample	**EDT [s]**	RT10 [s]	RT20 [s]	RT30 [s]
1A	**1,08**	1,19	1,20	1,20
1B	**0,91**	1,20	1,20	1,19
2A	**1,19**	1,16	1,22	1,22
2B	**0,97**	1,15	1,24	1,24
3A	**0,65**	0,80	0,85	0,87
3B	**0,82**	0,79	0,85	0,88
4A	**1,01**	1,08	1,24	1,24
4B	**0,65**	1,10	1,24	1,24
5A	**1,25**	1,28	1,42	1,40
5B	**0,85**	1,28	1,42	1,42

1.2.2. IRs with different RT10

Table 2 presents the values of the objective parameters for the sound samples used in the experiment that aimed to investigate the impact of changing the RT10 value on the perception of reverberation length. The difference in RT10 values between the samples is greater than 0,15 s and the difference between the values of the other parameters: EDT, RT20 and RT30 is less than 0,06 s.

Table 2: Measured values for different RT10

pair/ sample	EDT [s]	**RT10 [s]**	RT20 [s]	RT30 [s]
1A	0,98	**1,14**	1,27	1,31
1B	1,02	**1,30**	1,32	1,31
2A	1,13	**1,31**	1,30	1,28
2B	1,08	**1,07**	1,25	1,26
3A	0,71	**1,04**	1,12	1,15
3B	0,68	**0,86**	1,07	1,19
4A	0,81	**1,05**	1,41	1,41
4B	0,85	**1,28**	1,42	1,42
5A	0,59	**0,90**	1,18	1,34
5B	0,55	**0,73**	1,17	1,34

1.2.3. IRs with different RT20

Table 3 displays the values of the objective parameters for the sound samples used in the experiment that aimed to investigate the impact of changing the RT20 value on the perception of reverberation length. The difference in RT20 value between the samples is greater than 0,15 s and the difference between the values of the other parameters, that is EDT and RT10 is less than 0,02 s. As observed, the differences in the values of RT30 fall outside of the established limit. This can be attributed to the nonlinear shape of the IRs. When the RT20 value exceeds both the EDT and RT10 values, the RT30 value is further increased. This indicates that the RT30 parameter may not be as reliable a measure of perceived reverberation length as the other parameters under consideration.

Table 3: Measured values for different RT20

pair/ sample	EDT [s]	RT10 [s]	**RT20 [s]**	RT30 [s]
1A	0,67	0,79	**1,08**	1,19
1B	0,67	0,80	**0,85**	0,87
2A	0,63	0,89	**1,11**	1,14
2B	0,63	0,88	**1,37**	1,63
3A	0,65	0,93	**1,14**	1,21
3B	0,66	0,92	**1,37**	1,53
4A	0,64	0,77	**0,79**	0,79
4B	0,63	0,78	**0,98**	1,06
5A	0,71	1,04	**1,12**	1,15
5B	0,70	1,03	**1,38**	1,45

1.2.4. IRs with different RT30

Table 4 shows the values of objective parameters for sound samples when the effect of changing the RT30 value on perception of reverberation length was investigated. The difference in RT30 value between the samples is greater than 0,15 s and the difference between the values of the other parameters, that is EDT, RT10 and RT20 is less than 0,06 s.

Table 4: Measured values for different RT30

pair/ sample	EDT [s]	RT10 [s]	RT20 [s]	**RT30 [s]**
1A	0,21	0,48	0,67	**0,77**
1B	0,20	0,48	0,67	**0,96**
2A	0,76	1,05	1,30	**1,35**
2B	0,73	1,06	1,32	**1,55**
3A	0,63	0,79	1,23	**1,32**
3B	0,63	0,82	1,26	**1,49**
4A	0,72	1,13	1,53	**1,68**
4B	0,76	1,15	1,49	**1,52**
5A	0,69	1,01	1,32	**1,32**
5B	0,65	0,96	1,31	**1,81**

1.3. Participants

The experiment was conducted with 105 participants who had normal hearing. Among them, eight were younger than 20 years, 45 were aged between 20 and 29 years, 19 were aged between 30 and 39 years, 25 were aged between 40 and 49 years, and five were older than 50 years. The experiment was conducted during the sound engineering training sessions at an industry conference for sound engineers and music producers. Therefore, all participants can be considered experienced in assessing the reverberation length and having the ability to perceive the subtle structures of reverberation.

1.4. Procedure

The experiment was conducted using an internet website as a platform for presenting the stimuli to the participants. The test is still available online at the address: http://77production.pl/ankieta-poglosy/. The sound was delivered through a MOTU M2 interface which had hardware volume control and the participants used Focal Listen Pro headphones to listen to the stimuli. However, a small percentage of the listeners (less than 10%) used their own headphones for the test.

It is important to control for variables other than the ones being studied in an experiment to ensure that the results are valid and reliable. Therefore, instructing participants to focus only on the length of the reverberation helps to minimize the influence of other parameters on their perception of the reverberation. Prior to the test, participants were instructed that the question only pertained to the length of the reverberation and not to other acoustic parameters such as timbre, ASW Apparent Source Width), LEV (Listener Envelopment), etc.

During the experiment, participants were presented with pairs of sound samples in which the values of three reverberation time parameters were kept constant while the value of the parameter under test was varied. For each of the investigated parameters: EDT, RT10, RT20 and RT30 five pairs of “stop-chord” and five pairs of “running” sound samples were prepared. The participants were allowed to listen to each sound sample in a pair multiple times before providing their answer. The sound level was initially set to 65 dB, but the participants were free to adjust the volume during the test. The participants were asked to determine which sound sample in a pair had a longer perceived reverberation time. The correctness of the participants' responses was based on the consistency of their perceived change in reverberation length with the change in numerical value for the specific reverberation time parameter under test.

In this study, correct responses were determined based on whether the participant's perceived change in the length of reverberation was consistent with the actual change in the numerical value of the tested parameter. Specifically, if the participant correctly identified which sample had longer reverberation when the tested parameter was increased, the response was considered correct. Conversely, if the participant identified the sample with shorter reverberation when the tested parameter was increased, the response was considered incorrect.

4. RESULTS

Figure 1 presents the results for running reverberation samples, while Figure 2 presents the results for the stop-chord reverberation samples. The values expressed in the Figures represent the percentage of correct answers for the parameter under the test for all presentations given by all test participants.

To assess whether the responses given by the listeners were based on chance, a binomial test was performed to compare the proportion of correct answers against a value of 0.5. The results indicated statistical significance in almost all cases ($p<0.05$), with the exception of the "RT30 running" condition where both answers were equally frequent (263 and 262). The results showed that for the sound samples with "running" reverberation, correct responses were obtained in 61%, 58%, 72%, and 50% of cases for the EDT, RT10, RT20, and RT30 parameters, respectively. For the stop-chord reverberation sample, the corresponding values were 27%, 55%, 90%, and 77% for the EDT, RT10, RT20, and RT30 parameters, respectively. The parameter with the highest agreement between the change in its value and the perceived length of reverberation was RT20, for both the running and stop-chord reverberation samples. Additionally, the highest proportion of correct answers was obtained for RT20 for both types of reverberation samples.

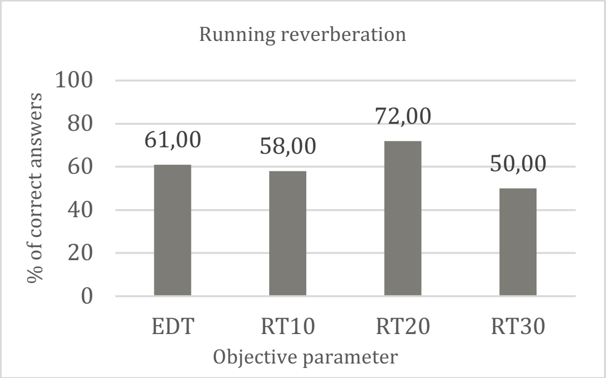

Figure 1: Correct answers for "running" reverberation

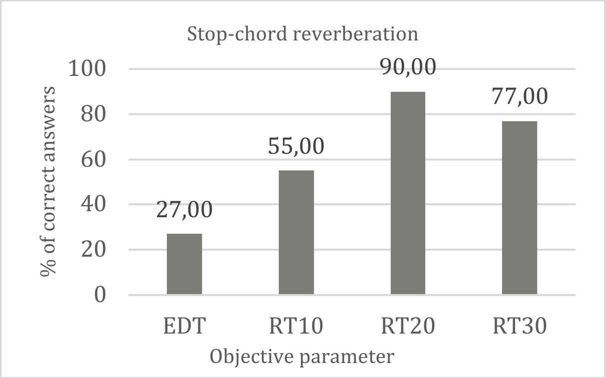

Figure 2: Correct answers for "stop-chord" reverberation

5. DISCUSSION

In the evaluation of "running" reverberation, the RT20 parameter showed the highest level of agreement between the change in its value and the subjectively perceived reverberation length. Specifically, 72% of the participants provided answers that were consistent with the expected result based on changes in RT20. The other parameters, in order of decreasing performance, were EDT with 61% correct answers, RT10 with 58% correct answers, and RT30 with 50% correct answers. Although statistical significance was obtained for responses related to the RT10 and RT30 parameters, response values of just over 50% cannot be considered significant for the assessment of reverberation length. Therefore, the results suggest that RT20 is the most relevant parameter in the evaluation of reverberation length for running reverberation.

In the case of "stop-chord" reverberation, the highest level of agreement between the change in the value of the parameter and the subjectively perceived reverberation length was also obtained for the RT20 parameter, with a score of 90% correct answers. The following parameters were RT30, RT10, and EDT with 77%, 55%, and 27%, respectively. Once again, the results indicate that RT20 is the best predictor of reverberation length. It is noteworthy that the number of correct answers for RT30 is also high, higher than for any parameter in the "running" reverberation part of the study. However, RT10 with 55% of correct answers cannot be considered as a reliable predictor of reverberation length. It is also interesting to note the negative correlation between the increase in the parameter value and the subjective evaluation of reverberation extension for EDT, with only 27% of correct answers. Nevertheless, this still indicates the high influence of the parameter value on the assessment of reverberation length. Furthermore, the difference in relevance assessment between EDT and RT10 when assessing reverberation length is also noteworthy, despite both parameters defining the same decay slope and being at the first part of the IR.

Significance tests were conducted for all decay assessment parameters in both "running" and "stop-chord" reverberation modes, and statistical significance was observed. However, the RT30 parameter, which is the most widely used according to global measurement standards, exhibited the lowest significance for the "running" reverberation mode, while the RT10 parameter showed the lowest significance for both "running" and "stop-chord" reverberation modes. Notably, a negative correlation was found between impulse samples that differed in their EDT value, which is of particular interest. Similar relationship was found in the study [5], however in this study the relationship was confirmed for a larger number of samples. Furthermore, an increase in the EDT value while maintaining the values of other parameters does not correlate with subjective feeling of longer reverberation.

We need to stress that the obtained results are not consistent with existing studies on the perception of reverberation length in rooms without AAES [4, 7]. This may suggest that the perception of reverberation with double-slope IRs is also different from the perception of more linear decay slope reverberations. Further investigations are necessary to obtain a definitive answer

regarding the impact of AAES on reverberation perception. This study primarily focused on double-slope decay IRs generated by AAES and provides a glimpse into the unresolved issue of the connection between various objective measures of reverberation and its subjective perception by humans.
Finally, the survey results confirm the different perception of reverberation length for impulse and continuous audio samples. Such an observation is consistent with a data from literature [21].

6. CONCLUSIONS

This study highlights the limitations of relying solely on objective parameters as measurements of acoustic quality. The results indicate that the perception of reverberation is complex and cannot be reduced to a simple relationship between objective parameters and subjective evaluation. Thus, the widely used objective parameter measurement standards may not fully capture the perception process and do not account for the individual differences in perception. In light of these findings, it is suggested that the acoustic design of enclosures should take into account the perception of human listeners and not rely solely on objective measures. The inclusion of subjective evaluations in the acoustic design process may lead to more accurate assessments of acoustic quality and ultimately improve the acoustic experience for listeners.
Below enumerated the detailed findings from the study:

- The connection between the subjective perception of reverberation and any of the objectively measured parameters is not a simple one-to-one relationship.
- The study did not provide definitive evidence to support the dominance of the EDT value in assessing reverberation length for double-slope reverberations generated by AAES, as observed in prior research on reverberation with a more linear IR shape.
- The presence of double-slope IRs in reverberations suggests the possibility of a similar relationship for other double-slope IRs, such as those resulting from the use of coupled chambers.
- Further research is necessary to establish the generalizability of the findings to other types of double-slope IRs.
- At the same time, it should be remembered that the perception of reverberation length is more complex and does not depend only on the change of the value of a single parameter. All the parameters: RT10, RT20 and RT30 were considered relevant in assessing the length of reverberation.
- The highest agreement was obtained for parameter RT20 for both “running” and “stop-chord” reverberations and it can therefore be considered the parameter that best correlates with the sense of reverberation length for all signals.

It should be emphasized that although the perception of reverberation length for halls with and without the AAES may vary, the change in reverberation length is clearly perceptible by the listeners, making it possible to conclude that the use of AAES to change reverberation length in concert halls is effective.
Since we confirmed that “running” and “stop-chord” reverberations are perceived differently, further research must be carried out in this area to find the possible objective measures of this phenomenon. Comparing the results will help determine which evaluation mechanism is dominant: whether the length of reverberation is evaluated during the course of a musical piece or during the breaks in the piece, when the decay of the reverberation is clearly audible.

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