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Quantification and Subjective Perception of Varying Reflection Densities in Measured Room Impulsed Responses

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QUANTIFICATION AND SUBJECTIVE PERCEPTION OF VARYING REFLECTION DENSITIES IN MEASURED ROOM IMPULSE RESPONSES

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This project focuses on quantifying and testing the subjective perception of reflection densities, or the number of reflections per second, from different room impulse responses. The widely used room acoustic metric, reverberation time, is linked to the perceived reverberation in a room. Two different rooms having the same reverberation time, though, can have different reflection densities in their room impulse responses, and this difference in reflection density may affect how listeners perceive spatial impression in rooms. To investigate how sensitive humans are to a change of reflection density, this paper first reviews assorted parameters for quantifying reflection density from measured room impulse responses. A number of parameters are considered that can impact a metric for reflection density, including the resolution due to the sampling frequency, the applied time window, and the cut-off level for including a reflection in the count. A developed quantification method is subsequently applied to select a range of reflection densities from realistic room impulse responses for use in a perceptual study on determining the maximum audible reflection density by humans. Both speech and clapping signals are convolved with the assorted impulse responses for testing. Results from this study provide further insight on how humans perceive sound in rooms through linking temporal behavior of reflections with spatial perception.

1. Introduction

Reflection density is simply the number of reflections per second. When an impulse is emitted in a room, that impulse signal is reflected by the room boundaries and these reflections increase in number as a quadratic function of time [1]. After a certain time has passed, the reflection density is high and the human auditory sensor can no longer distinguish one reflection from another because of the limited human auditory time resolution [2]. In previous research, the maximum audible reflection densities reported vary between 1000 and 10000 reflections per second [3]-[7]. These studies used impulse responses and a 20 kHz bandwidth. However, one does not commonly hear impulse responses in the everyday environment. Recently, Krueger et al. [8] tested speech signals, and the maximum audible reflection density was found to be lower, around 300 reflections per second. Since the maximum audible reflection density using speech appears to be different from testing with impulse responses, further assessment of the maximum audible reflection density using speech or music is needed.

The studies mentioned above have been primarily interested in generating artificial reverberation in rooms. However, the aim of this study is not to add artificial reverberation, but to quantify reflection densities from more realistic room impulse responses and understand how humans perceive those reflection densities. It is trickier to quantify reflection density from measured room impulse responses because reflection density grows with time in real rooms, so reflection density could be changed by the settings of the time window. Also, reflection density depends on how true reflections in real impulse responses are defined. Recently Jeon et al. [9] presented a method to quantify reflections in impulse responses for evaluation of scattered sounds in concert halls. In that paper, they counted the number of local maxima as reflections under the assumption that they have enough time between them. However, these local maxima can overlap and build some arbitrary peak structure depending on the sampling frequency; unfortunately they do not provide information on the sampling frequency used in their study. Also, the study set a -20 dB cut-off level for determining reflections; however, this number seems to be selected arbitrarily. One should be careful that the background noise level is at least 20 dB lower than the direct sound level, or else such a method will count local maxima under the background noise level. More work on methods to quantify reflection density from realistic impulse responses needs to be conducted, through determining appropriate time windows, cut-off levels, and how to deal with reflection density changing over time.

2. Quantification of reflection density

The reflection density may be calculated theoretically based on global characteristics of an enclosure including volume and boundary surface area, as given in Equation (1) [3].

$$\bar{n} = \frac{cS}{4V} \tag{1}$$

where $\bar{n}$ is mean reflection density, c is speed of sound in [m/s], S is the surface area in [m^2], and V is the volume of the room in [m^3]. This equation assumes a diffuse field which is not always easily achieved in real rooms. In this paper, a method for calculating reflection density of more realistic room impulse responses is examined based on assorted combinations of time window and cut-off level. The method is applied to twenty different sizes of same shaped rooms (the sample room provided in ODEON) with controlled reverberation time (T_{30}) of 1 sec, as simulated in ODEON.

2.1.1 Room impulse response (RIR) generation

The room model 'Example room' from ODEON was used to simulate room impulse responses. The general room configuration and sound source and receiver locations are shown in Figure 1**Error! Reference source not found.**. The relative location of the source and receiver in each room was maintained across all twenty room sizes.

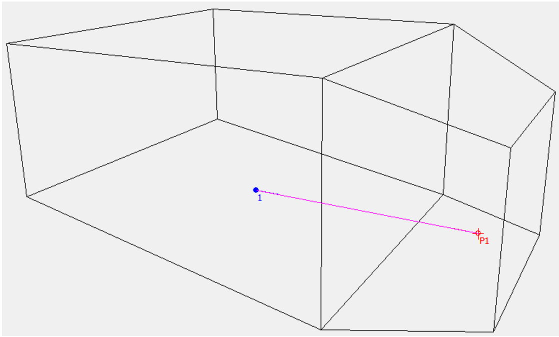
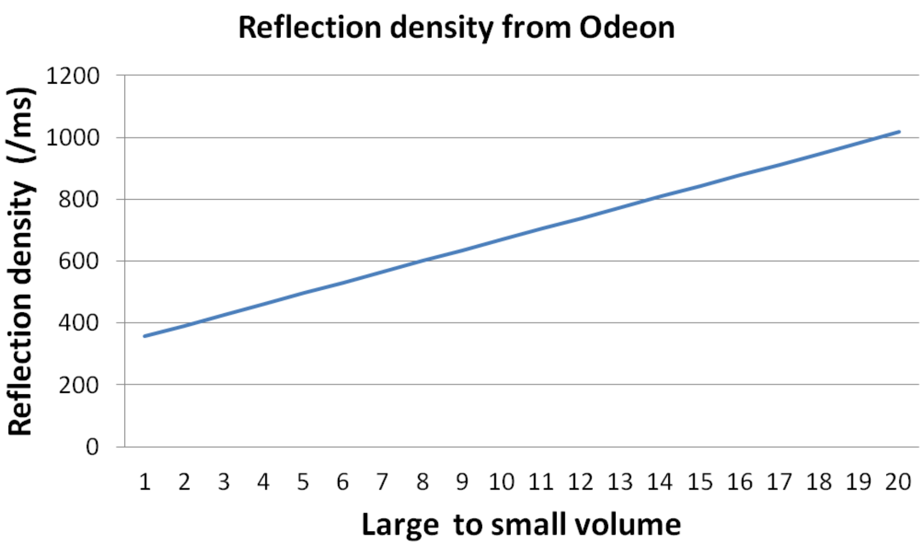


Figure 1 Example room and location of source and receiver

The number of late rays in ODEON was set to be 10000. Twenty different sizes of the example room were generated, and the sizes were adjusted to have a linear variation of reflection density as calculated from ODEON based on the classic reflection density equation for diffuse fields (Figure 2**Error! Reference source not found.**). The largest volume corresponding to room #1 is 1268 m^2.



Room #	Reflection Density (/ms)
1	357
2	391
3	427
4	460
5	496
6	530
7	564
8	601
9	634
10	670
11	705
12	740
13	774
14	809
15	844
16	878
17	912
18	948
19	983
20	1017

Figure 2 Theoretical reflection density calculated for each of the different room sizes

2.1.2 Proposed method to quantify the reflection density

Reverberation time (T_{30}) was controlled to be 1 sec from 63 Hz to 8000 Hz in all cases by adjusting surface absorption uniformly. Since ISO 3382-1 [10] recommends a source level of 45 dB above the background noise level for T_{30} measurements, most measured impulse responses are expected to have a source level of at least 35 dB above the background noise level. For this reason, the cut-off level of -35dB was selected and -50dB was also selected for comparison. Time windows were tested in increasing 50 ms increments, out to a maximum of 1 second, and then reflections above each cut-off level were counted until the limit of each time window was reached. An example of this method is sketched in Figure 3.

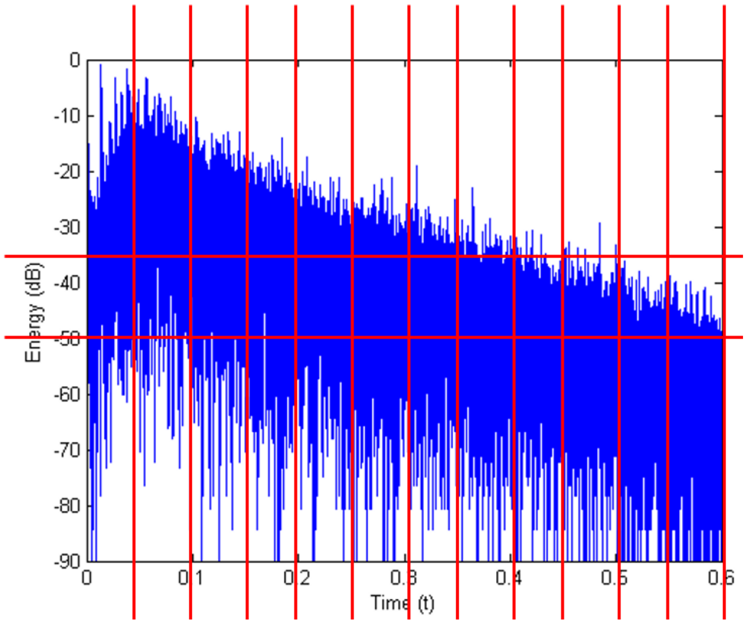


Figure 3 Sample impulse response with overlaying grid of different cut-off levels and time windows, used to quantify reflection density

The number of reflections was determined from a Matlab program, applied to the ODEON simulated impulse responses. The sampling frequency of the impulse responses was 44000 Hz. Figure 4 depicts the total number of reflections from the different combinations of cut-off levels and time windows for each of the 20 rooms. The number of reflections is expected to have a linear or gradual change by room size variation; however, the result shows many fluctuations, likely due to inherent randomness in these simulated impulse responses. Since the number of reflections from this method was not as consistently linear as desired, the number label for each room has instead been used in this paper. More work on quantifying reflection density is continuing.

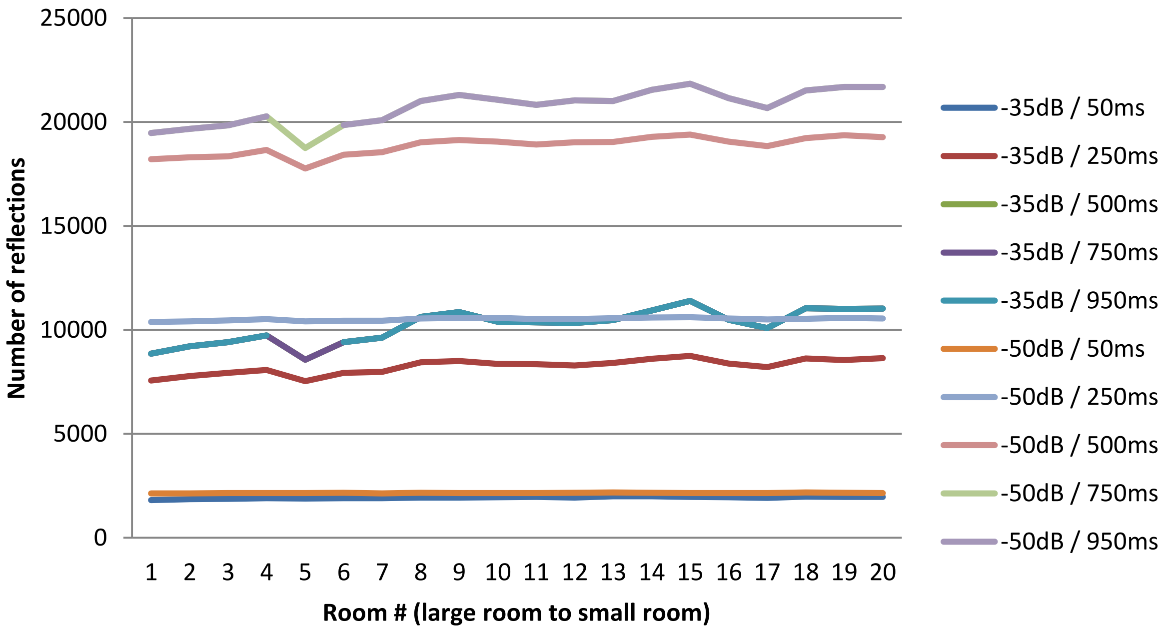


Figure 4 The number of reflections counted for the 20 variously sized rooms (with 1 being the largest room and 20 being the smallest in size), based on the cut-off level and time window shown in the legend

3. Subjective experiment

3.1 Test procedure

A three-alternative forced-choice (3AFC) method combined with a one-up two-down subjective testing method was used to determine the upper limit of distinguishable audible reflection density from the twenty simulated rooms. The 3AFC method presents two identical reference reflection density samples (taken to be the highest reflection density among the samples) and one comparison reflection density sample for each trial. The testing program enforces that the participant listens to these three sound samples three times in a row, and the subject is then asked to choose the one sample that sounds different from the other two. The order of the two reference samples and one comparison sample is randomly arranged for each trial. The reflection density used for samples in this study are shown in Table 1. Since the proposed quantification method was not available, reflection densities provided by ODEON are shown.

Table 1 Reflection density (RD) of sound samples, based on ODEON-provided calculation.

RD label	Relative volume	RD (/ms)	RD label	Relative volume	RD (/ms)
1	1	357	11	0.146	705
2	0.771	391	12	0.130	740
3	0.595	427	13	0.113	774
4	0.488	460	14	0.098	809
5	0.433	496	15	0.090	844
6	0.315	530	16	0.082	878
7	0.275	564	17	0.074	912
8	0.232	601	18	0.066	948
9	0.197	634	19	0.058	983
10	0.170	670	20 (Reference)	0.050	1017

The reflection density of the comparison sample in each trial begins with the lowest reflection density (or most different from the reference sample) and changes based on the one-up two-down method. If a subject answers incorrectly, which means he/she chooses one of the reference samples as being the one different among the three presented, the difference between the reference and comparison increases (up), which means the comparison sample's reflection density decreases. If a subject selects correct answers two times consecutively, the difference between comparison and reference reflection density decreases (down), which means the comparison sample's reflection density increases. When reversals in direction occur, those reflection densities are marked and subsequently averaged after the designated number of reversals is reached to determine the upper limit of distinguishable reflection density. A subject's response from the one-up two-down test method is depicted in Figure 5; five reversals were recorded for this study.

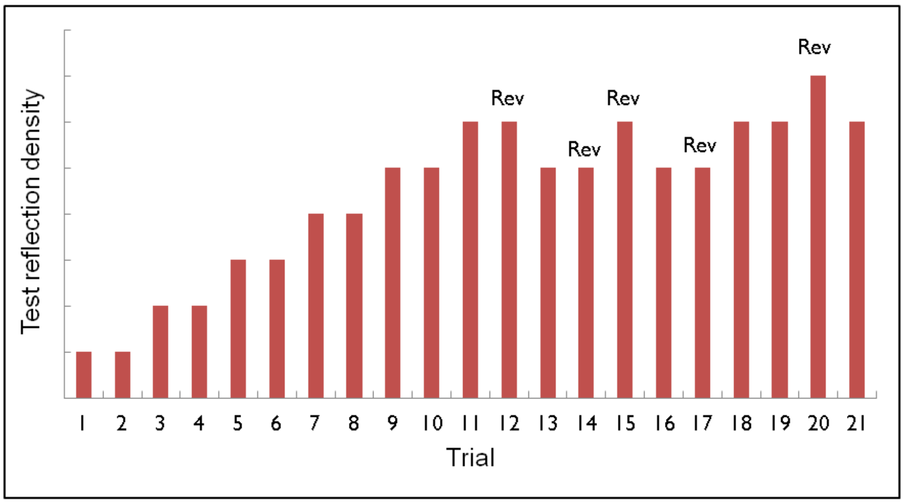


Figure 5 Sample of one-up two-down subjective testing method with five reversals

3.2 Participants

Twenty listeners participated in the subjective test. All listeners had pure tone thresholds above 25 dB hearing level between 250 and 8000 Hz. Listeners provided informed consent for their participation in the study and were paid for their time.

3.3 Test Stimuli

Two kinds of source signals were used: clapping and speech. Both the clapping and speech sound samples were cropped from signals that came from the ODEON version 11 database. The clapping signal included five claps, while the speech sentence stated 'When you are applying for a job, you need to have a good resume prepared'. These source signals were convolved in ODEON with the room impulse responses simulated from twenty different sizes of rooms, presented in Section 2. Because the reverberation time (T_{30}) was controlled to be 1 sec in all cases, reverberation time did not act as an additional cue in the subjective testing.

Due to the differences in volume and distance between source and receiver, the loudness of the convolved signals from each room was different. To maintain the same loudness, an algorithm ITU-R in Adobe Audition was used. This algorithm normalizes the perceived loudness considering the frequency dependence of human hearing, and proved to work better than other ways of normalizing loudness, such as peak normalization or RMS normalization.

Prepared test stimuli were presented to participants on a laptop using a custom Matlab GUI. The tests were performed in a sound booth and presented over headphones (Sennheiser HE60) to the subjects.

4. Results and analysis

The results show relatively large variation among subjects; Figure 6 indicates the actual trial responses from a few of the subjects tested.

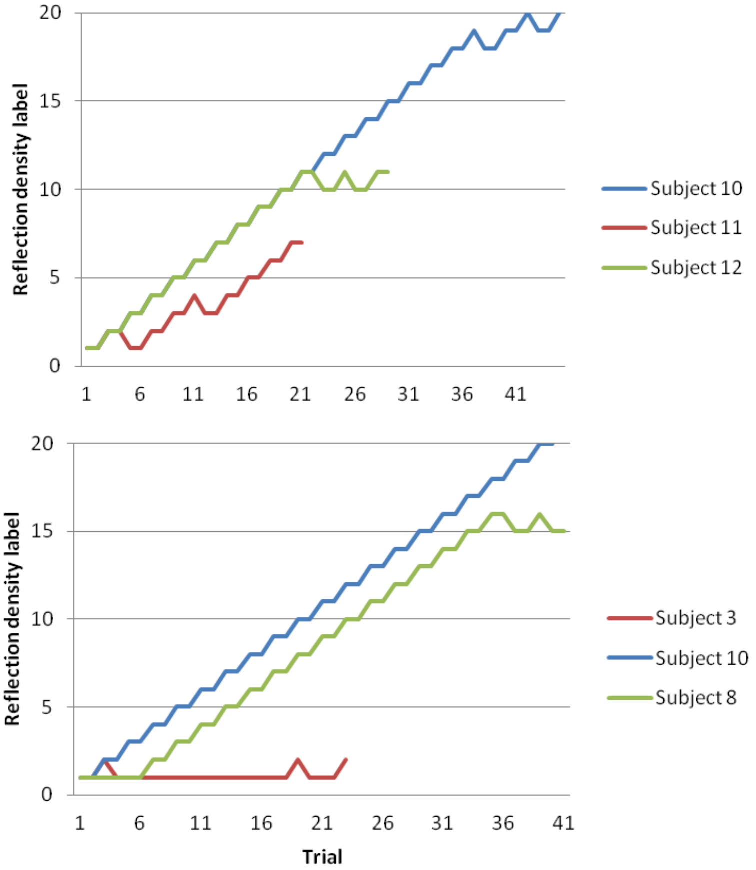


Figure 6 Sample of results for clapping case (top) and speech case (bottom)

Among the five reversals recorded for each subject, only the last three were included in the calculated average, as many of the first reversals occurred early in the trials when subjects appeared to be still understanding the test methodology. The mean reflection density room label from the clapping sounds was room 9.60 with a standard deviation of 5.31; the mean reflection density room label from the speech sounds was 9.71 with a standard deviation of 6.77. A t-test was performed and these two cases appear to have no significant difference ($p=0.943$). A few subjects were able to distinguish almost all comparison samples. Since the variance is large, this may indicate that there was another cue in the test samples, other than reflection density, that some could use to distinguish samples. The additional cues could be frequency spectrum differences, small loudness differences, or differences in another room acoustic parameter. There were also a few subjects who did not reach above room label 3 so apparently could not distinguish differences at all, or did not understand the testing instructions.

Previous research had suggested that there would be a significant difference in the upper limit of distinguishable reflection density between the speech signal and the more impulsive clapping sound, as reflections from the speech signal would overlap with the ongoing signal. However, as mentioned above, the results of these two cases (clapping and speech) show no significant difference in this investigation.

5. Conclusion

A method for quantifying reflection density from realistic room impulse responses based on a set time window and cut-off level has been suggested, but requires further development. Also the upper limit of audible reflection density using both clapping and speech signals was examined through subjective testing. The upper limit of audible reflection density between clapping and speech signals was not found to be significantly different.

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