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ABSTRACT

This study seeks to quantify the just noticeable difference (JND) of reverberation time (RT) using band-limited noise. ISO 3382-1 lists the JND of reverberation metrics at 5% based on work by Seraphim (1958). However, others have found the JND of RT to be higher from 6% to 39%. Many of these studies utilized band-limited stimuli, e.g. speech, music motifs and band-limited noise. A previous study by the authors conducted on 30 subjects using white noise demonstrated a JND of RT at 22%. To further verify these results and investigate potential upward frequency masking, the present study was conducted following the same methodology but using octave-band limited noise centered at 1000 Hz instead of white noise. Binaural room impulse responses (BRIR) were created from the Elmia concert hall in ODEON by uniformly varying absorption coefficients across all surfaces and frequencies to achieve the desired RTs. The desired RTs varied around three reference values (1, 2, and 3 seconds), with eight samples approaching the reference RT from below and another eight approaching from above, at 4% intervals of the reference RT. Auralizations of the BRIRs and 500 ms band-limited noise were randomly presented in a computer-based testing program using a three-interval one-up two-down forced choice method, while interleaving six staircase sequences (3 reference RT X 2 downward vs. upward approaching direction). Subjects were individually tested in a sound attenuated booth using headphones with flat frequency response. Results are presented and compared against those previously obtained using white noise.

1 INTRODUCTION

The just noticeable difference (JND) of reverberation time (RT) quantifies the minimum change in RT that can be readily perceived. The JND is a useful metric when performing cost-benefit analysis on projects where the RT of a space is to be altered. The present accepted value for the JND of RT, published in ISO 3382-1, is 5% for reverberation metrics[1] based on work conducted by Seraphim[2]. However, more recent research conducted in this area has produced a wide range of JND values using a variety of stimuli. The present study seeks to investigate the JND of RT using more refined stimuli and test procedures.

This study utilized a three-alternative forced-choice up-down adaptive method to determine the JND of RT. The stimuli used were a set of auralizations of 1000 Hz octave-band limited noise using impulse responses of a computer-simulated concert hall with incrementally varying RT. The impulse responses were created by varying the absorption coefficients, which were uniform across all octave band frequencies and on all surfaces.

2 BACKGROUND

The seminal work conducted by Seraphim[2] and published in 1958 established the 5% JND of RT that is currently widely recognized. This work has drawn some speculation, though, and many studies have been conducted since then to confirm or disprove the findings. Niaounakis and Davies[3] reported difference limens (DLs) of 0.026 ± 0.022 seconds for music samples presented in a room with variable acoustics and 0.057 ± 0.005 seconds for recordings made in the same room presented over loudspeakers. The first test relied heavily on auditory memory, though, and the RT intervals used were not uniform. Meng, Zhao, and He[4] tested 34 subjects using motifs played on typical Chinese instruments with base level RTs of 1, 2, 3, and 4 seconds. JNDs ranged from 21.2% to 39.0% of the baseline RTs. They further studied the JND of noise length using white noise with lengths of 0.3 to 8 seconds. Those results were less than 10%, which coincide better with Seraphim's study.

Frissen, Katz, and Guastavino[5] performed a series of experiments using noise, music, and speech as stimuli. Their results agreed generally with Seraphim's findings with JNDs less than approximately 10%. They also concluded that choice of stimuli does not significantly affect the JND of RT. Billon and Embrechts[6] used two experimental approaches and three stimuli (noise, speech, and music) to determine the JND of RT. Their results agreed roughly with those of Frissen et al. Karjalainen and Järveläinen[7] found the JND of RT for a simple exponential decay of Gaussian noise, and a convolution of the exponential decay and a speech signal. The resulting JNDs ranged from 3.3% to 12.5%.

Several issues arose from these previous research studies, however, which the present study seeks to address. First, most of the experiments used the method of constant stimuli which requires subjects to perform pairwise comparisons. With this method the subjects are likely to respond correctly to 50% of the trials merely by guessing. Second, in some studies the signals used were not typical of what would be encountered in realistic environments (e.g., true exponential decay, digital reverberation simulator). On the other hand, the work done by Niaounakis and Davies likely introduced auditory memory as a confounder, because the signals, although realistic (e.g., room with variable RT) were presented separately with intermissions that were much longer than the duration of auditory memory. The methodology of the present study addresses the issues that arose from previous research.

3 METHODOLOGY

3.1 Stimuli

Subjects were presented with auralizations of 500 millisecond octave-band limited noise centered at 1000 Hz. The auralizations were created by convolving the octave-band limited noise with binaural room impulse responses (BRIRs) created in the acoustical room simulation software ODEON. ODEON was chosen because of its accuracy proven through rigorous round-robin testing[8-11]. The detailed model of the Elmia concert hall has the flexibility to create a wide range of RT, while still retaining the characteristics of a realistic environment. The most realistic approach, in which the surface absorptions of a real room are altered to systematically vary the RT, was not practically feasible for the present study and would likely confound the results due to short auditory memory, as identified in the Niaounakis and Davies study.

The stimuli cases were created based on three reference RTs of 1, 2, and 3 seconds. Each case contains eight test stimuli which have RTs that approach the reference in increments of 4% either from above or below the reference as shown in Table 1.

Table 1: RTs of stimuli at 4% increments for three reference RTs and two approach directions

Case 1: 1 sec from below	**Case 2: 1 sec from above**	**Case 3: 2 sec from below**	**Case 4: 2 sec from above**	**Case 5: 3 sec from below**	**Case 6: 3 sec from above**
1.00	1.00	2.00	2.00	3.00	3.00
0.96	1.04	1.92	2.08	2.88	3.12
0.92	1.08	1.84	2.16	2.76	3.24
0.88	1.12	1.76	2.24	2.64	3.36
0.84	1.16	1.68	2.32	2.52	3.48
0.80	1.20	1.60	2.40	2.40	3.60
0.76	1.24	1.52	2.48	2.28	3.72
0.72	1.28	1.44	2.56	2.16	3.84
0.68	1.32	1.36	2.64	2.04	3.96

The different RTs were achieved by uniformly varying the absorption coefficients of the materials in the model across all surfaces and frequencies. The lengths of the auralizations were also carefully controlled so that stimulus duration remained constant for each reference RT.

3.2 Procedures

A three-alternative forced-choice paradigm was employed. In this procedure subjects are asked to compare three auralizations and indicate which sounds different from the other two. The two identical auralizations are always a reference RT (1, 2, or 3 seconds). A transformed up-down adaptive method was also used, specifically the “one-up, two-down” adaptive method. In this method one incorrect response increases the difference in RT between the test auralization and references, while two correct responses decreases the difference. This combined three-alternative transformed up-down adaptive method finds the point on the psychometric curve at which participants perceive the difference in RT correctly 67% of the time – a point which lies close to halfway between 33% (from simply guessing between three choices) and 100%.

In addition, each reference RT is approached from above and below. When the reference RT is approached from above, the test auralization begins with a RT longer than that of the references and, with every two consecutive correct responses, descends toward the reference RT in 4% increments. When approached from below, the test auralization begins with a RT shorter than that of the references and, increases toward the reference RT.

The RT of the test auralizations was logged after each reversal. A reversal is defined as a change in direction with respect to the reference RT and an example is shown in Figure 1. Each case was terminated after five reversals. The overall JND of RT is calculated as the average of the five reversals across six cases.

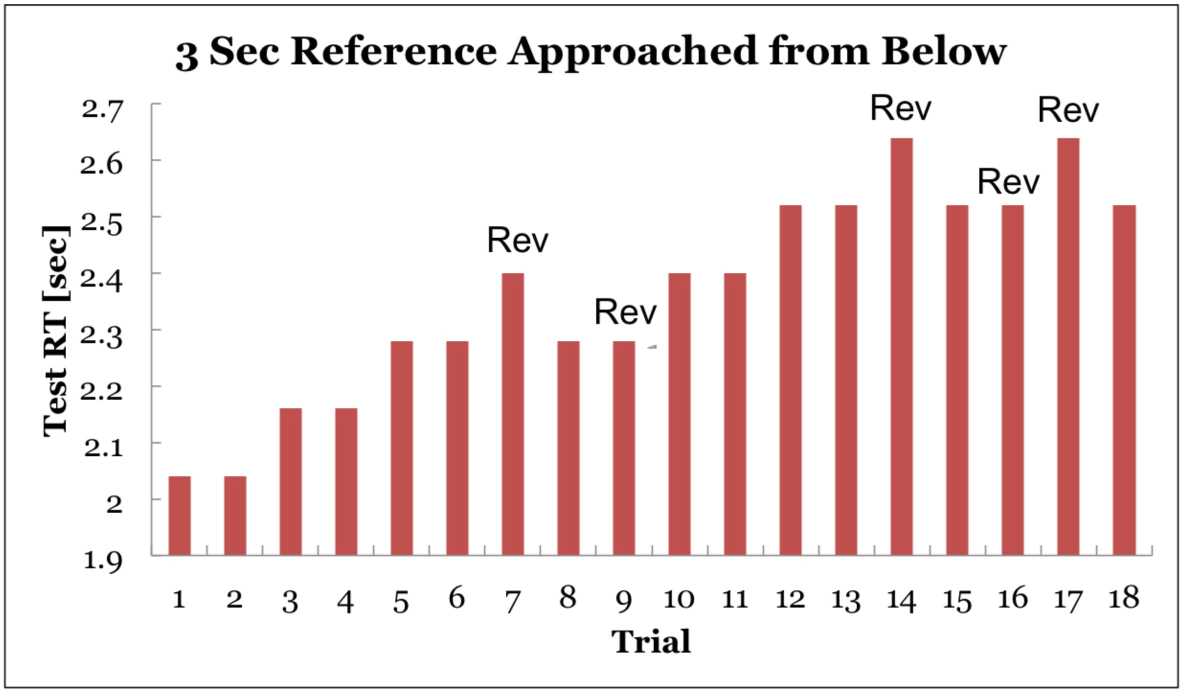

Figure 1: Two-up, one-down reversals example

The subjective testing was executed using a custom computer program that randomly interleaves trials from the six cases to prevent subject conditioning. The stimuli were presented over frequency-neutral headphones in an acoustically-treated listening booth. The sound level of the stimuli was calibrated at L_{max} of 75 dBA and constant for all subjects.

3.3 Subjects

At the submission of this proceedings paper, four subjects (three females and one male) were tested using the procedures described above. Eligible subjects were required to be at least 19 years of age and have a minimum of three years of musical training or experience. All subjects were given hearing screenings and deemed to have hearing thresholds at or below 25 dB(HL) at every octave band from 125 Hz to 8 kHz.

4 RESULTS

The mean JND of RT for each of the six cases across four subjects is shown in Table 2. The overall JND of RT is found to be 24.5% with a standard deviation of 6.09%

Table 2: JND of RT for 1000 Hz octave-band limited noise bursts

	Reference RT approached from below Mean [%] (Std. Dev. [%])	**Reference RT approached from above Mean [%] (Std. Dev. [%])**
1 sec Reference RT	22.8 (8.30)	27.8 (4.48)
2 sec Reference RT	22.6 (9.29)	25.8 (3.29)
3 sec Reference RT	20.2 (7.71)	27.6 (3.49)
Average	21.9 (8.43)	27.1 (3.75)
Overall Average	24.5 (6.09)	

The results for a total of 10 subjects will be presented at ISRA 2013.

5 DISCUSSION

For comparison purposes, the results of a previous study conducted using the same procedures outlined above are presented. It utilized 500 millisecond white noise bursts instead of band-limited noise bursts.

A total of 30 subjects (11 females and 19 males) were tested and an overall JND of RT of 22.3% with a standard deviation of 6.14% was calculated across all six cases. Results from the six individual tests (3 reference RTs x 2 approach directions) are presented in Table 3.

Table 3: JND of RT for white noise bursts

	Reference RT approached from below Mean [%] (Std. Dev. [%])	**Reference RT approached from above Mean [%] (Std. Dev. [%])**
1 sec Reference RT	21.5 (5.71)	23.4 (6.63)
2 sec Reference RT	20.6 (6.03)	23.8 (6.50)
3 sec Reference RT	20.6 (6.10)	24.0 (5.83)
Average	20.9 (5.95)	23.7 (6.32)
Overall Average	22.3 (6.14)	

The pair-wise Pearson's correlation was calculated for the overall JND of RT, test duration, and gender. The only significant correlation was found between the overall JND of RT and test duration ($r = -0.34$, $p = 0.035$). No gender effect was found.

A repeated measures ANOVA was conducted between direction (auralizations approached the reference RT from above versus from below) and reference RT, both as within-subject factors. Results indicated a significant effect of direction, $F(1,28) = 9.27$, partial effect size $\eta^2 = 0.25$, $p = 0.005$. The overall JND of RT was found to be higher when the test auralizations began with longer RTs and approached the shorter reference RTs from above.

6 CONCLUSION

The overall JND of RT has been found to be 24.5% using 1000 Hz octave-band limited noise for RTs between one and three seconds. These preliminary results coincide with those obtained by Meng et. al.[4] and indicate the JND of RT is much higher than the widely recognized 5%[2].

The preliminary results also coincide with results of a previous study which used white noise as the stimuli, as described in the Discussion section. This agrees with the findings of Frissen et. al.[5] that the type of stimuli does not significantly affect the JND of RT.

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