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# Noise and acoustic conditions of premises for hearing impaired people in Korea

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**Hearing-impaired people need more stringent acoustic and noise requirements than normal-hearing people in terms of speech intelligibility and listening effort. Multiple guidelines recommend a maximum reverberation time of 0.4 s in classrooms, signal-to-noise ratios (SNR) greater than 15 dB, and ambient noise levels lower than 35 dBA. We measured noise levels and room acoustic parameters of 12 classrooms in two schools for hearing-impaired pupils, a dormitory apartment for the hearing impaired, and a church mainly for the hearing impaired in the Republic of Korea. Additionally, subjective speech clarity and quality of verbal communication were evaluated through questionnaires and interviews with hearing-impaired students in one school. Large differences in subjective speech perception were found between younger primary school pupils and older pupils. Subjective data from the questionnaire and interview were inconsistent; major challenges in obtaining reliable subjective speech perception and limitations of the results are discussed.**

Primary subject classification: 51.1; Secondary subject classification: 56.2, 69.2

## 1 INTRODUCTION

Hearing impaired people, even in aided conditions, suffer more from noisy and bad acoustic conditions than normal hearing counterparts. For example, aided hearing-impaired listeners have consistently poorer speech intelligibility performance than normal-hearing listeners<sup>1</sup>. Combined effects of reverberation and noise on the intelligibility of sentences for the hearing impaired were investigated using speech transmission index (STI)<sup>2</sup>, concluding that for hearing-impaired subjects, every 3 dB hearing loss for speech in noise can be compensated for by an increase of 0.1 in STI. Since many hearing-impaired subjects have hearing losses larger than 3 dB for speech in noise, Plomp and Duquesnoy concluded that the hearing impaired need much shorter reverberation times and lower background noise levels than the normal hearing<sup>3</sup>. To implement this conclusion in classrooms, the reverberation time would need to be reduced tremendously<sup>3</sup>. Yang and Hodgson also investigated speech intelligibility scores for normal-hearing and hearing-impaired people in two different signal-to-noise ratio (SNR) conditions: 0 and 5 dB. They concluded that hearing-impaired listeners were more adversely affected by reduced speech-to-noise level differences<sup>4</sup>.

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6 Accordingly, the American Speech-Language Hearing Association (ASHA) published “Guidelines  
7 for addressing acoustics in educational settings,” that called for background noise levels not to exceed  
8 30 dBA, reverberation times not to exceed 0.4 seconds, and an overall teacher SNR of more than 15 dB  
9 <sup>5</sup>. Generally, these specifications were confirmed by the American National Standards Institute (ANSI),  
10 which recommended in ANSI S12.60 <sup>6</sup> that background noise level not exceed 35 dBA, reverberation  
11 time (RT) not exceed 0.6-0.7 seconds, and a SNR of +15 dB. Another study recommended more  
12 detailed guidelines for the hearing-impaired pupils, such as noise criteria (NC) of 20 or less, with a  
13 modified clarity ratio of  $C_{\text{arrival time}+20\text{ms}}$  of 10 dB or more, and STI greater than 0.75 <sup>7</sup>.

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16 However, several on-site measurements have reported that these acoustic requirements are rarely  
17 fulfilled in reality. For example, Crandell and Smaldino reported that none of the 32 classrooms  
18 measured in the US met recommended criteria for noise levels and only 9 out of the 32 US classrooms  
19 showed RTs of 0.4 s or less<sup>8-9</sup>. No acoustic measurements have been conducted in Korean school  
20 buildings and important premises for hearing-impaired listeners, so it is still not known if these acoustic  
21 requirements are fulfilled or not.  
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24 The primary objective of this study is to investigate the objective room acoustic measures of  
25 premises mainly intended for hearing-impaired people in Korea to see whether the suggested guidelines  
26 by ASHA are fulfilled in those rooms. Moreover, it is natural and crucial to study if the users’  
27 subjective perception of acoustics is well in line with the objective acoustic parameters measured in the  
28 classrooms. We managed to collect subjective answers in seven classrooms at one school via  
29 questionnaires and individual interviews. With these data, we studied a correlation between subjective  
30 perception of acoustics and objective room acoustic measures and subjective speech clarity results for  
31 hearing aid users (HA) and cochlear implant users (CI), separately. A cochlear implant is a small  
32 electronic device that partially restores hearing through a surgical procedure for sufferers of profound  
33 hearing loss, for whom a hearing aid is of no or little benefit. Having such correlations between on-site  
34 subjective and objective data in several classrooms helps draw meaningful criteria for satisfactory  
35 acoustic conditions for the hearing impaired in terms of speech perception. This is particularly  
36 important because the objective speech parameter used in this study,  $C_{50}$ , a widely used speech clarity  
37 parameter based on the useful-to-detrimental energy ratio concept, has rarely been used in studies  
38 aimed for hearing-impaired pupils.  
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## 45 **2 EVALUATION METHOD**

46 This chapter describes the rooms investigated, and how the objective and subjective data were  
47 collected in this study.  
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### 49 **2.1 Rooms for survey**

50 Three different types of premises for the hearing impaired in the Republic of Korea were  
51 evaluated: one church, one dormitory apartment, and 12 classrooms of two schools, as shown in Fig. 1.  
52 Youngnak church of the deaf is a church mainly for hearing impaired people, which was built in 2006.  
53 Its dimensions are approximately 23 m, 17 m, and 4 m, ending up with a volume of 1564 m<sup>3</sup>.  
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4 Nongawon dormitory (built in 2007) is a residential facility, where 34 hearing-impaired people  
5 live. Three people share an apartment that has a living room, bathroom, kitchen, and three bedrooms.  
6 One apartment of the dormitory was measured.  
7

8 The two large schools for hearing impaired children that were measured are Seoul National School  
9 for the Deaf (SNSD) and Seoul Samsung School (SS). The main building of SNSD was built in 1988,  
10 accommodating 95 students enrolled from kindergarten to high school classes. SS was built in 1976,  
11 accommodating 109 students, from kindergarten to high school. Five classrooms in SNSD and seven  
12 classrooms in SS were measured.  
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## 15 16 **2.2 ISO 3382 measurements for objective parameters**

17 Objective quantification of room acoustic conditions was conducted according to ISO 3382-2<sup>10</sup>. An  
18 omnidirectional loudspeaker (B&K type 4292) was used as a sound source. Impulse responses were  
19 measured by Dirac Room Acoustics Software (B&K type 7841) using exponential sweep signals of  
20 either 0.67 s or 1.35 s to ensure a 35 dB dynamic range for properly measuring  $T_{20}$ , a reverberation time  
21 measure using a decay range of 20 dB.  
22

23 For Younknak church, reverberation time  $T_{20}$  and STI values were calculated from the impulse  
24 responses measured at 13 source–receiver (S-R) combinations. The loudspeaker was located at 3  
25 potential locations of a priest in the chancel of the church and microphones were distributed in the nave  
26 area. The height of the source was set to 1.7 m and the height of the microphone was 1.2 m from the  
27 floor to represent a seated person. These heights were maintained in the other rooms.  
28

29 For the dormitory, only  $T_{20}$  was used for a general assessment of room acoustics. We measured  
30 seven S-R combinations in the living room and the large bedroom, and four S-R combinations in the  
31 small bedroom. A smaller number of S-R combinations in the small bedroom was due to its small size  
32 to keep the distance from the microphone to the nearest reflecting surface and the sound source to 1 m  
33 and 1.5 m, respectively<sup>10</sup>.  
34

35 For the classrooms,  $T_{20}$ , STI, and speech clarity  $C_{50}$  are the main parameters used for general  
36 acoustics and speech clarity evaluation. In all classrooms, the omnidirectional loudspeaker was located  
37 at a potential teacher’s position and microphones were distributed in the pupils’ seating area. At least  
38 two source locations were used in all the classrooms. We aimed to sample minimum six S-R  
39 combinations in each room, but in some small rooms like the science room in SNSD it was only  
40 possible to collect four S-R combinations.  
41

42 For the sake of simplicity, the measured objective parameters were spatially averaged across the S-  
43 R combinations and averaged across the octave bands centered from 125 Hz to 4 kHz, and only the  
44 mean values are presented in Section 3. All measurements were carried out in December 2018.  
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## 52 **2.3 Questionnaire and Interviews**

53 To collect the users’ subjective responses, a paper-based questionnaire was distributed. The  
54 questionnaire concerned the users’ acoustic satisfaction regarding loudness, speech clarity, and  
55 annoyance due to external and internal noise sources. The respondents could choose one answer on a  
56 five-point verbal rating scale. For example, the speech clarity question for classrooms was formulated  
57 as: “How clear do you hear the teacher’s voice during class? (the quality of speech transmitted to you  
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4 from the teacher)”, and the rating scales were: 1=extremely bad, 2=bad, 3=fair, 4=good, 5=extremely  
5 good. The noise annoyance question for the church was: “how much are you disturbed by noise during  
6 the mass?”, with rating scales: 1=extremely disturbing, 2=disturbing, 3=slightly disturbing, 4=not  
7 disturbing although noise heard, 5=no noise heard. The loudness of sermon was determined in the  
8 following question: “How loud is the sermon?”, on a bipolar scale of: 1=very weak, 2=a little weak,  
9 3=appropriate, 4=a little loud, 5=very loud.

10  
11 The questions were answered in December 2018; 41 answers were collected from the church, 15  
12 answers from the dormitory, and 60 answers collected from SS. The number of answers collected  
13 differed from classroom to classroom. The minimum number collected was six in the elementary  
14 classroom 6-1 (the first classroom of the year six students), whereas the maximum number was 10 in  
15 the science room and elementary classroom 5-2, high school 3-1, and high school 3-2.

16  
17 Additional interviews were conducted in SS. Hearing-impaired people usually receive many  
18 questionnaires and tend not to answer them very seriously. The school covers a broad age range from  
19 kindergarten children to high school students; younger children may not understand as thoroughly as  
20 older students do. The hearing-impaired pupils have more difficulty in reading than in speech  
21 communication because of the limited vocabulary and lack of reading capability<sup>11-13</sup>. For this reason,  
22 the additional explanation in spoken and sign language is widely applied for questionnaires targeted for  
23 hearing-impaired listeners. Therefore, the interviews with the pupils who used the measured classrooms  
24 were included to complement questionnaire results. Individual interviews are known to be more precise  
25 than group interviews for two reasons. First and foremost, the interviewees are hearing-impaired  
26 children, who might face even bigger challenges in group conversations, e.g., lack of concentration and  
27 difficulties in conversing in a big group. Second, the interview results could possibly be biased by  
28 certain strong opinions in a group interview. However, due to a time limitation, we ended up with a  
29 group interview in one classroom, High school 3-2. The interviews were conducted in the same  
30 classrooms in May 2019, meaning that the interviewees were different from the questionnaire  
31 respondents because Korean school year runs from March to February. The number of interviewees in  
32 each classroom varied from two (science room) to seven (high school 3-2).

### 3 RESULTS

33  
34 In this section, the noise and acoustic conditions of the rooms are presented in terms of objective  
35 parameters and subjective responses from the questionnaires and interviews.

#### 3.1 Church

36  
37 The reverberation time  $T_{20}$  of the church hall is shown in Fig. 2.  $T_{20}$  in the 63 Hz octave band is  
38 additionally indicated as suggested by<sup>14</sup>. The mean reverberation time  $T_{20}$  was 0.74 s, averaged across  
39 the frequency bands from 63 Hz to 8 kHz. This reverberation time is still much shorter compared to  
40 other places of worship. The average of STI values across 13 source-receiver combinations was 0.69  
41 with a standard deviation of 0.03, signifying a good speech communication quality. This value  
42 corresponds to the qualification scale “C” of high speech intelligibility according to IEC 60268-16<sup>15</sup>.  
43 Note that the same standard states that modern churches have a nominal STI value of 0.58 (Category  
44 “E”). Therefore, it is concluded that this church has better speech intelligibility than other modern

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4 churches, but no comparable acoustic data regarding churches for hearing-impaired people were  
5 available.  
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7 The noise level in an unoccupied condition was quite stable across the church space, varying from  
8 33 dBA to 35 dBA. With an open window, 39 dBA was measured. The unoccupied noise level satisfies  
9 the ASHA recommendation and Beranek's recommendation of 38 dBA for small churches<sup>16</sup>.  
10

11 Based on the questionnaire results, the church was subjectively rated as fair-to-good in terms of  
12 speech clarity (mean speech clarity rating of 3.2). It was also rated as 'not disturbing' in terms of noise  
13 annoyance (mean noise annoyance rating of 4.4). However, the loudness of sermon was rated as  
14 slightly weak (mean speech loudness rating of 2.5). The subjective ratings are in line with the objective  
15 room acoustic parameters measured in the church.  
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### 18 **3.2 Dormitory**

19 The reverberation times in the rooms of the dormitory Nongawon are shown in Fig. 3. The longest  
20 reverberation time  $T_{20}$  averaged across the measurement points and frequency bands was 0.68 s in the  
21 living room, which is ascribed to the largest room volume and coupling to an open kitchen area. The  
22 big bedroom had an averaged  $T_{20}$  of 0.46 s and the small bedroom had an averaged  $T_{20}$  of 0.39 s.  
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25 Unoccupied noise levels were 34-38 dBA, which is close to what is recommended by ASHA, 35  
26 dBA. According to Beranek's recommendation of 38-48 dBA for bedrooms and residences for sleeping,  
27 resting, relaxing<sup>16</sup>, the background noise level in the dormitory rooms was sufficiently low.  
28

29 The subjective speech clarity was evaluated as fair-to-good (subjective score of 3.3) and noise  
30 annoyance was rated as slightly disturbing (noise score of 2.3). They commented that chair dragging  
31 noise, computers, and others conversation during night were particularly annoying.  
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### 34 **3.3 Classrooms at SNSD and SS**

35 In Fig. 4,  $T_{20}$  of the classrooms measured is shown as a function of frequency. It did not comply  
36 with the ASHA's reverberation time limit of 0.4 s. In general, SNSD had longer reverberation times  
37 than SS. In SNSD, the octave-band averaged  $T_{20}$  changed from 0.57 s to 0.75 s from classroom to  
38 classroom as shown in Fig. 4(a). In SS, the octave-band averaged  $T_{20}$  changed from 0.43 s to 0.66 s as  
39 shown in Fig. 4 (b) and Table 1. The noise levels in occupied conditions varied from 31 dBA to 42  
40 dBA. Unoccupied noise levels could not be measured due to a time constraint. In Fig. 5, the speech  
41 clarity  $C_{50}$  of the classrooms in SS is shown, which was used to make a correlation with subjective  
42 speech clarity scores from the questionnaire and interviews. STI scores in SS were 0.76 for the science  
43 room, 0.72 for the elementary classrooms 5-1, 5-2, and 6-1, 0.71 for high school 3-1, and 0.66 for high  
44 school 3-2 and middle school 1-1.  
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47 In Fig. 6, the subjective speech clarity scores from the questionnaire are plotted against the  
48 frequency averaged  $C_{50}$ . Note the subjective speech clarity rating scales were: 1=extremely bad, 2=bad,  
49 3=fair, 4=good, 5=extremely good. The subjective speech clarity scores were no smaller than 3,  
50 although the reverberation times of all classrooms exceeded the ASHA limit. When the data are divided  
51 into two age groups, primary school and secondary school pupils, one can observe that the primary  
52 school classrooms had objective clarity  $C_{50}$  values higher than 4 dB, and that there was a proportional  
53 relation between the objective clarity and subjective clarity. On the other hand, the secondary school  
54 classrooms had  $C_{50}$  values smaller than 4 dB, but the subjective clarity scores were quite high, between  
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4 3 and 4. One interpretation is that older students could understand the speech better than younger  
5 students even in more adverse listening conditions. There was no significant difference found between  
6 the hearing-aid users and cochlear-implant users in terms of subjective speech clarity. Due to a lack of  
7 statistical power, statistical analyses and regression models are not presented.  
8

9  
10 In Fig. 7, the subjective speech clarity scores from the interview are plotted against the frequency  
11 averaged  $C_{50}$ . The subjective speech clarity ratings from the interview were generally much higher than  
12 those from the questionnaire, except for the high school classroom 3-2, where a group interview was  
13 conducted. Admittedly, the reason for such a low clarity score in this classroom is unknown; it could  
14 possibly be ascribed to the group interview. The subjective scores from the interviews were consistently  
15 high and do not depend on  $C_{50}$ .  
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17 We hypothesized that such high subjective scores could be partly due to the fact that the hearing-  
18 impaired students did not have a decent reference/experience of good acoustic conditions. Therefore,  
19 we asked an additional question during the interview: could they perceive any acoustical difference in  
20 different spaces, such as playground, subway station, shopping mall and so on? As a result, most of  
21 them answered negatively; 63% answered ‘Never’. In Fig. 8, the relation between their subjective  
22 evaluation of speech clarity and self-evaluation of perceptual sensitivity to changes in the acoustic  
23 conditions is shown. The more insensitive to the acoustical changes they were, the higher the subjective  
24 speech clarity scores are.  
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#### 29 **4 DISCUSSION AND LIMITATIONS**

30 During the investigation, we found on-site evaluation of speech clarity, particularly from the  
31 hearing-impaired pupils, quite challenging for several reasons. (1) The number of collected answers  
32 was quite small. In this study, the sample size from the interview varied from 2 to 10 in each class. (2)  
33 The reliability of the answers from younger children is rather questionable, because they could have  
34 misunderstood the question about speech clarity due to lack of experience and vocabularies to describe  
35 the feeling related to the acoustic sensation. (3) Many do not have good references of good acoustics,  
36 and so they tend to overrate the speech intelligibility and clarity.  
37

38 We found two positive aspects of the Korean classrooms measured: (1) small number of students  
39 in class – normally less than six people –, (2) short distances from the teacher. Many rooms have  
40 typical dimensions of 4.8 m (D)  $\times$  6.3 m (W)  $\times$  2.7 m (H) and the distance from the teacher to the pupil  
41 is mostly within 2 m (shortest 1.3 m, longest 3.0 m). As also pointed out in the several previous studies  
42 <sup>17, 18</sup>, in a laboratory setting with auralized sound stimuli, cochlear implant recipients are rather  
43 insensitive to the acoustic conditions, but strongly prefer shorter source-to-listener distances. In those  
44 laboratory tests, the distances vary from 1 to 15 m <sup>17</sup> and 1-6 m <sup>18</sup>. To the best of the authors’  
45 knowledge, there are no other on-site subjective speech clarity data available for comparison.  
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47 We speculate that our interview results could be biased. Many children eventually answered that  
48 the subjective speech clarity in the class was ‘very good’, but the teachers spent a lot of time making  
49 them understand the speech clarity question, and more importantly, the teachers repeated the same  
50 question again and again until the children understood, which could be an indication that the speech  
51 clarity was not perfect. The reason for such a contradiction is not clearly understood by the authors. In  
52 addition, the expression for ‘high speech clarity/intelligibility’ in Korean can potentially be  
53 misunderstood as ‘hearing sufficiently loudly’.  
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## 5 CONCLUSIONS

The acoustic and noise conditions of several important rooms mainly used by hearing-impaired people in the Republic of Korea were characterized and compared to the ASHA guideline. Youngnak church had a reverberation time of 0.74 s averaged across the frequency bands and 13 source-receiver combinations and a mean speech transmission index of 0.69. According to IEC 60268-16, this church had higher speech intelligibility than typical modern churches, which is supported by the questionnaire answers. The unoccupied noise level satisfies the existing noise guidelines for the intended use.

Although the dormitory rooms for hearing-impaired people have no acoustic guidelines, the speech clarity was subjectively evaluated as fair-to-good. The reverberation time in the living room was 0.68 s and those in the bedrooms were shorter than 0.46 s. The unoccupied noise level in the dormitory ranged 34-38 dBA, but the residents had some complaints related to man-made noise sources, such as chair-dragging noise and conversations.

In the 12 classrooms measured in two schools, none satisfied the ASHA reverberation time requirement of 0.4 s, but no classrooms were subjectively evaluated to have bad speech clarity, which was surprising. The reverberation times in the classrooms ranged from 0.44 s to 0.75 s and STI values from 0.61 to 0.76. There was no statistically significant difference in the subjective speech clarity between HA and CI groups. The subjective speech clarity evaluation from questionnaires and interviews was inconsistent and the scores from the interviews were generally higher. We found that the older pupils in the secondary school evaluated the speech clarity highly even in more challenging acoustic conditions than those in the primary school. During the interviews, we also observed that the more insensitive to the acoustical changes, the higher the speech clarity scores. The noise level was measured only in occupied conditions, varying from 31 to 42 dBA, which seems sufficiently low, but without measurements in unoccupied conditions, it is hard to conclude the background noise and SNR condition in the school.

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Table 1—  $T_{20}$ , STI, and  $C_{50}$ , and subjective speech clarity results in SS.

		Science	Ele. 6-1	Ele. 5-2	Ele. 5-1	High 3-1	High 3-2	Mid. 1-1
Octave-band averaged $T_{20}$ (s)		<b>0.43</b>	<b>0.49</b>	<b>0.49</b>	<b>0.51</b>	<b>0.54</b>	<b>0.64</b>	<b>0.66</b>
Octave-band averaged $C_{50}$ (dB)		<b>7.4</b>	<b>4.6</b>	<b>4.9</b>	<b>4.9</b>	<b>3.7</b>	<b>3.1</b>	<b>2.6</b>
STI		<b>0.76</b>	<b>0.72</b>	<b>0.72</b>	<b>0.72</b>	<b>0.71</b>	<b>0.66</b>	<b>0.66</b>
Questionnaire	Speech Clarity	<b>3.9</b>	<b>3.0</b>	<b>3.3</b>	<b>3.0</b>	<b>4.0</b>	<b>3.5</b>	<b>3.8</b>
	No. of HA/CI among Pupils	7/3	2/0	3/4	1/0	2/2	3/3	2/2
	Speech Clarity from HA	3.9	3.0	3.3	3.0	4.0	3.3	4.0
	Speech Clarity from CI	4.0	-	3.3	-	4.0	3.7	3.5
Interview	Ratio CI/HA	1/1	3/1	4/1	2/4	1/2	5/2	1/2
	Speech Clarity	<b>4.5</b>	<b>4.5</b>	<b>5</b>	<b>4.6</b>	<b>5</b>	<b>3.6</b>	<b>5</b>
	Speech Clarity from HA	<b>4</b>	<b>3</b>	<b>5</b>	<b>4.8</b>	<b>5</b>	<b>4</b>	<b>5</b>
	Speech Clarity from CI	<b>5</b>	<b>5</b>	<b>5</b>	<b>4.5</b>	<b>5</b>	<b>3.4</b>	<b>5</b>

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### List of Figure Captions

- Fig. 1— Photos of the measured rooms: (a) Youngnak church, (b) Nongawon dormitory, (a) classroom of SNSD.*
- Fig. 2— Reverberation time  $T_{20}$  and its standard deviation (error bar) in Youngnak church.*
- Fig. 3— Reverberation time  $T_{20}$  in the rooms of Nongawon domitory.*
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- Fig. 5 — Clarity  $C_{50}$  in SS.*
- Fig. 6— Subjective speech clarity scores in the classrooms from the questionnaire as a function of  $C_{50}$ .*
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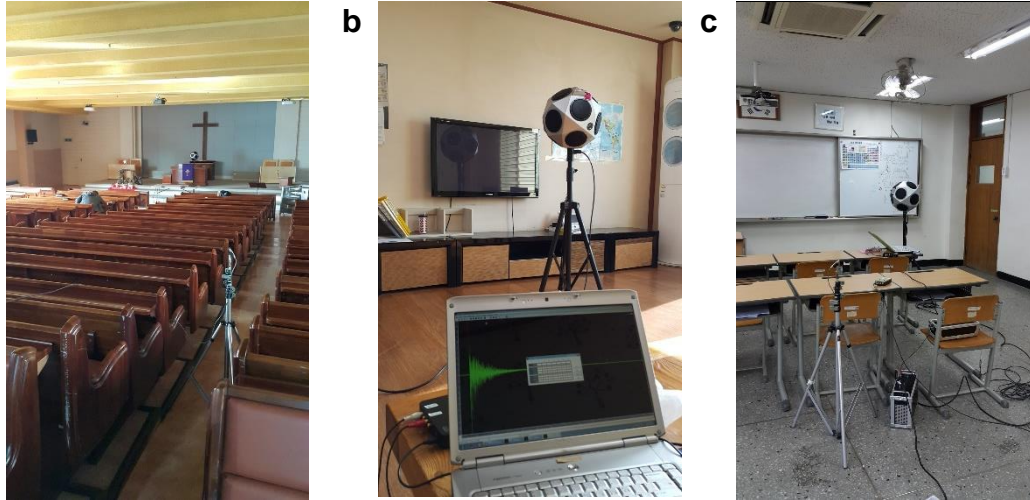


Fig. 1— Photos of the measured rooms: (a) Youngnak church, (b) Nongawon dormitory, (a) classroom of SNSD.

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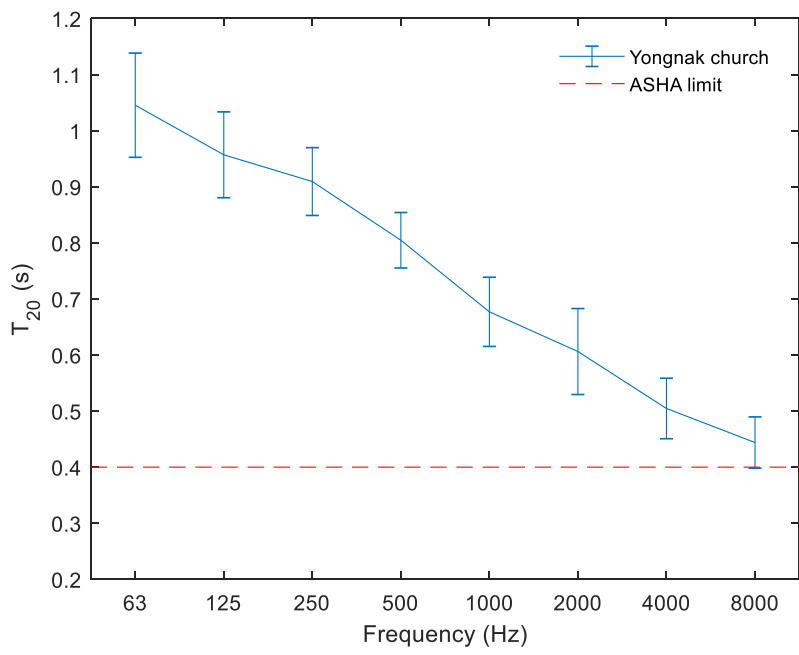


Fig. 2— Reverberation time  $T_{20}$  and its standard deviation (error bar) according to frequency in Youngnak church.

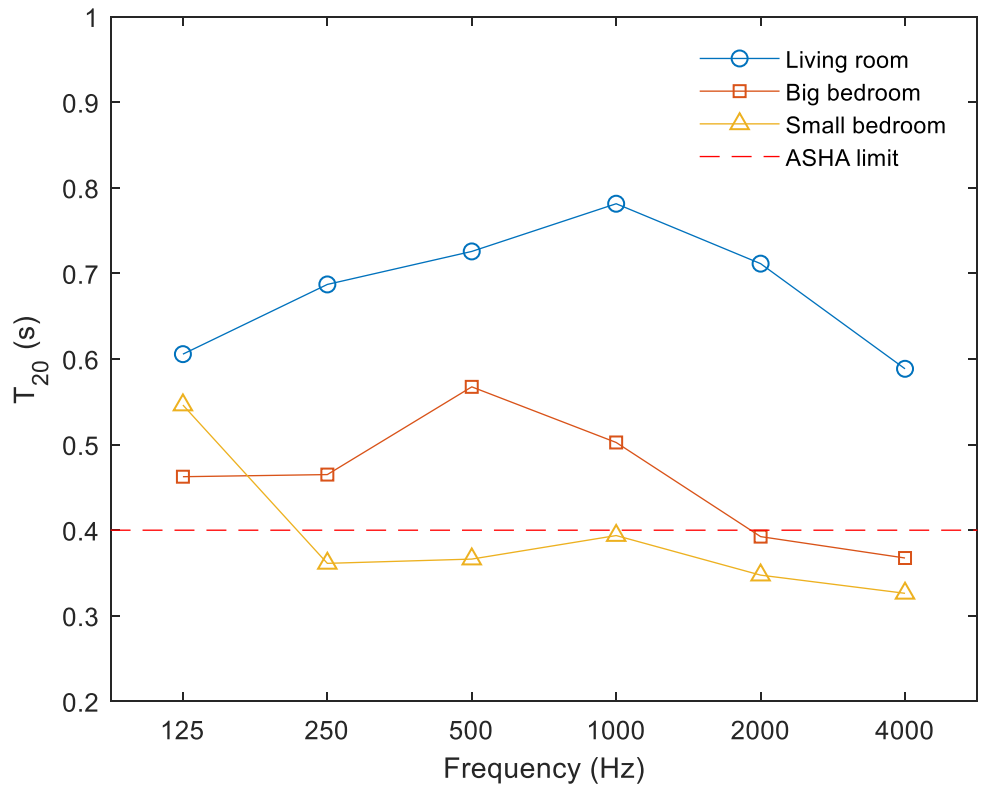
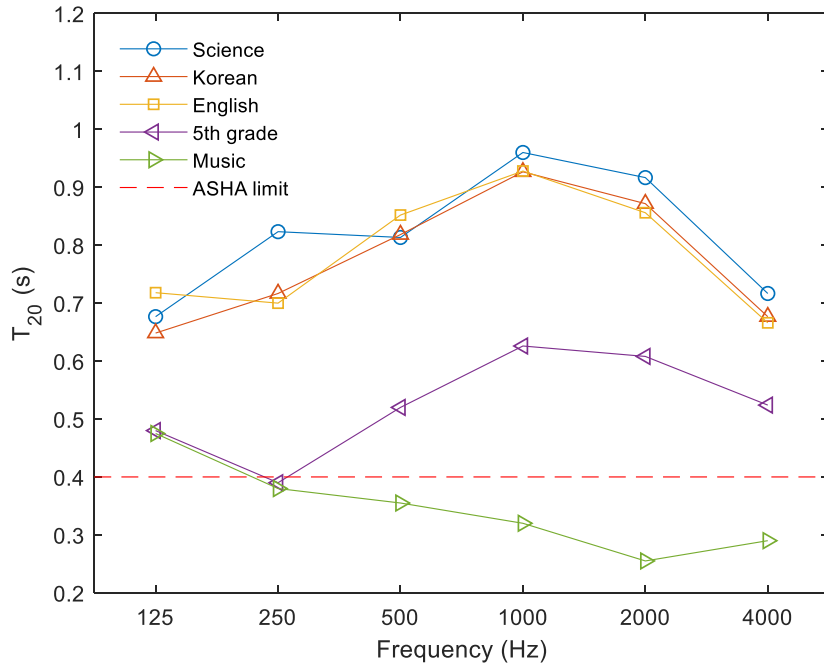


Fig. 3 — Reverberation time  $T_{20}$  according to frequency in the rooms of Nongawon domitory.



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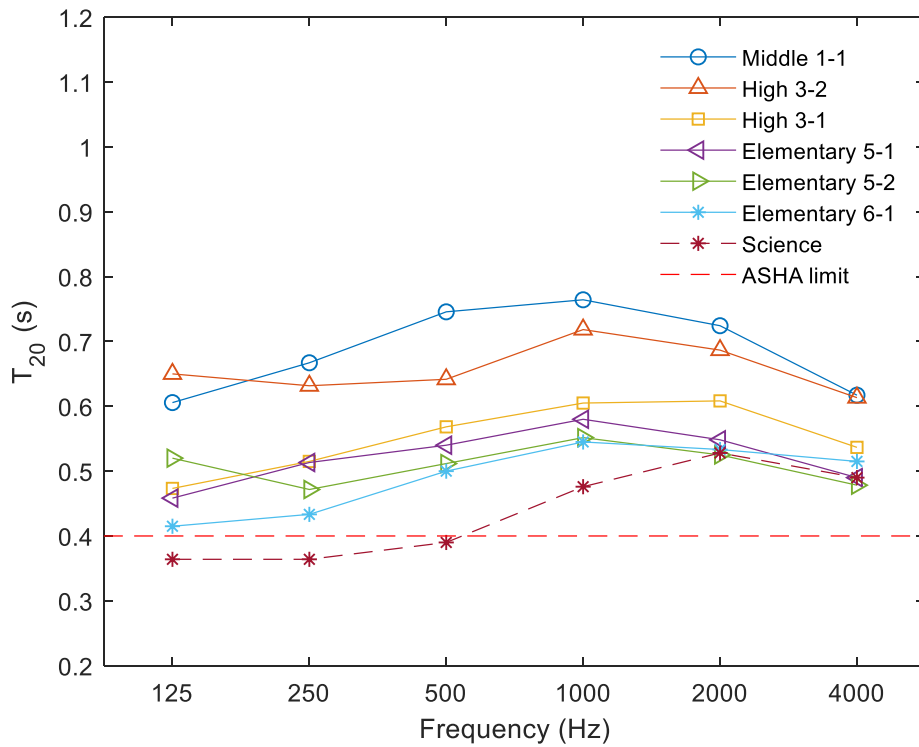


Fig. 4 — Reverberation time  $T_{20}$  according to frequency: (a) SNSD, (b) SS.

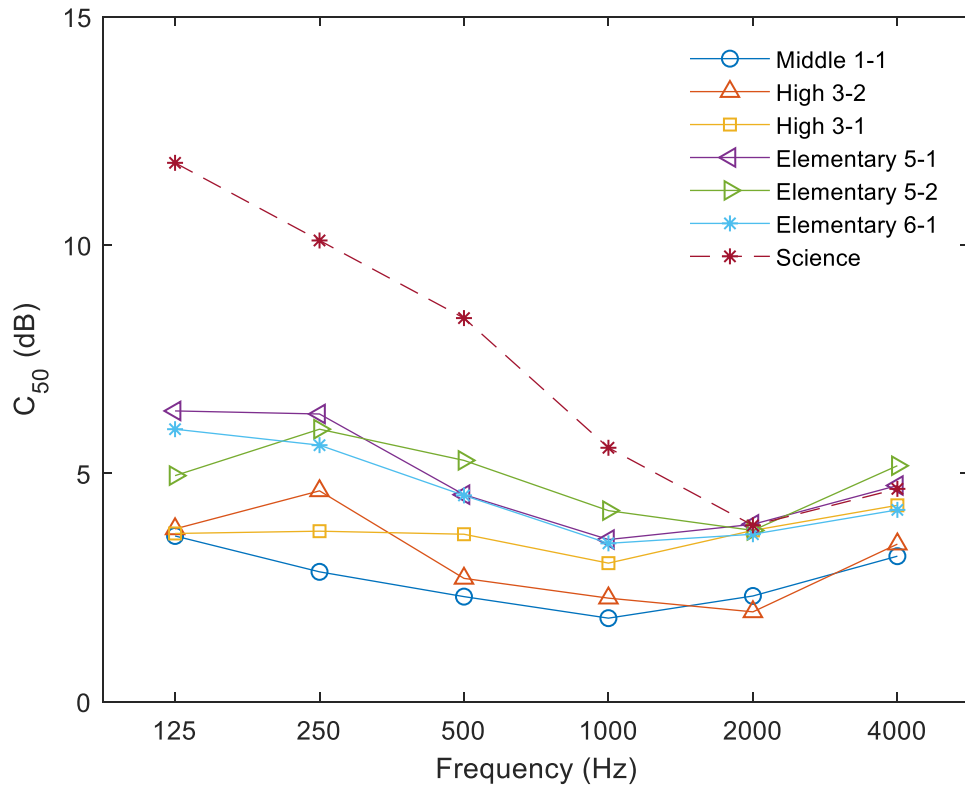


Fig. 5 — Clarity  $C_{50}$  according to frequency in SS.

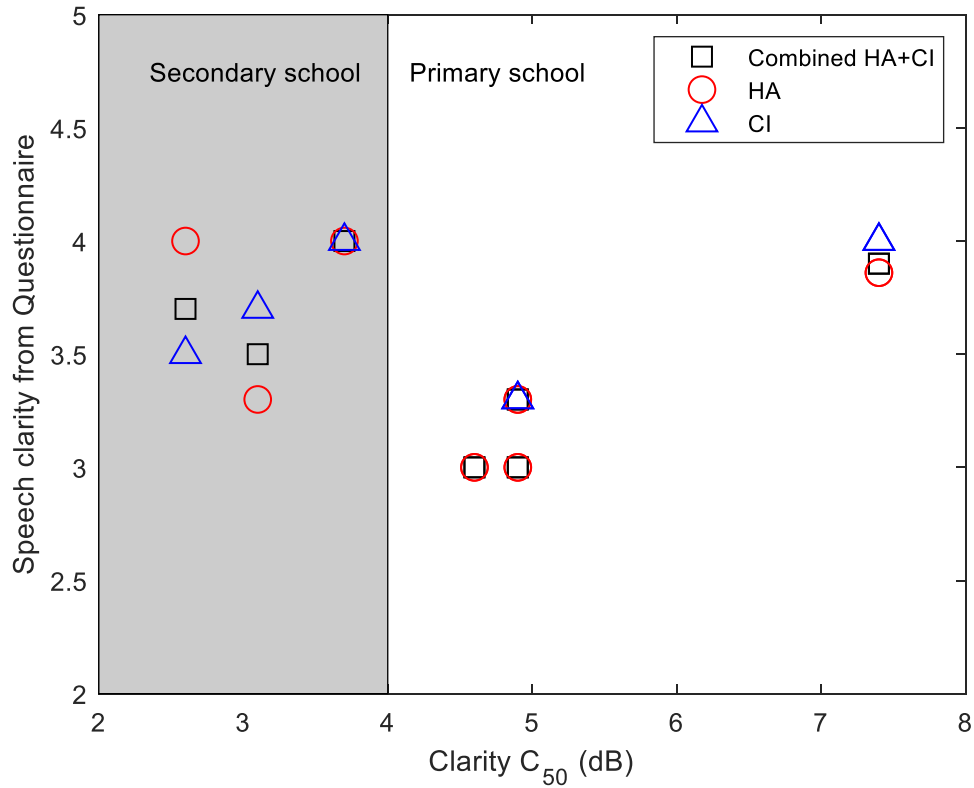


Fig. 6— Subjective speech clarity scores in the classrooms from the questionnaire as a function of  $C_{50}$  (HA: Hearing aids, CI: Cochlear implant).

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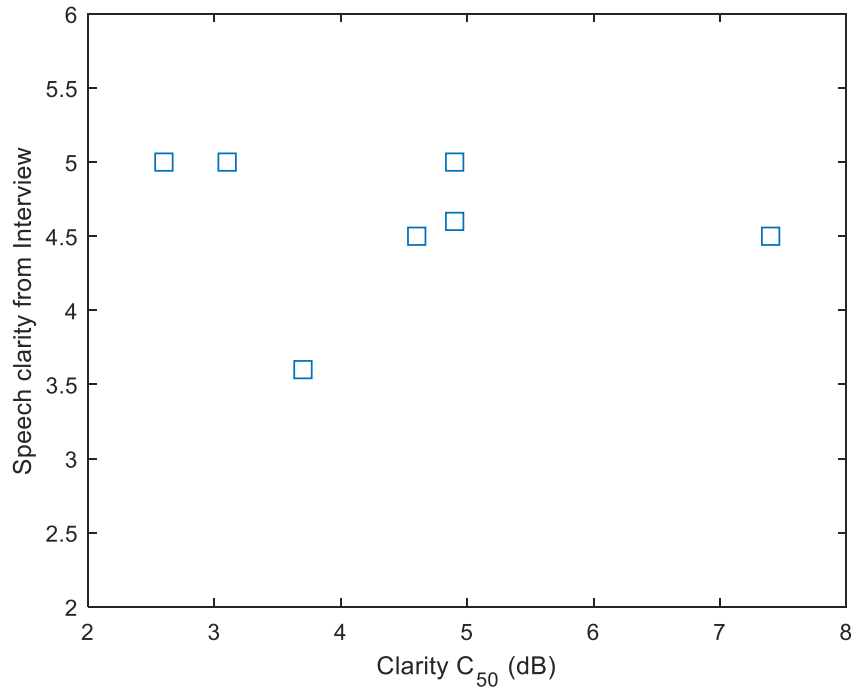


Fig. 7— Subjective speech clarity scores in the classrooms from the interview as a function of  $C_{50}$ .

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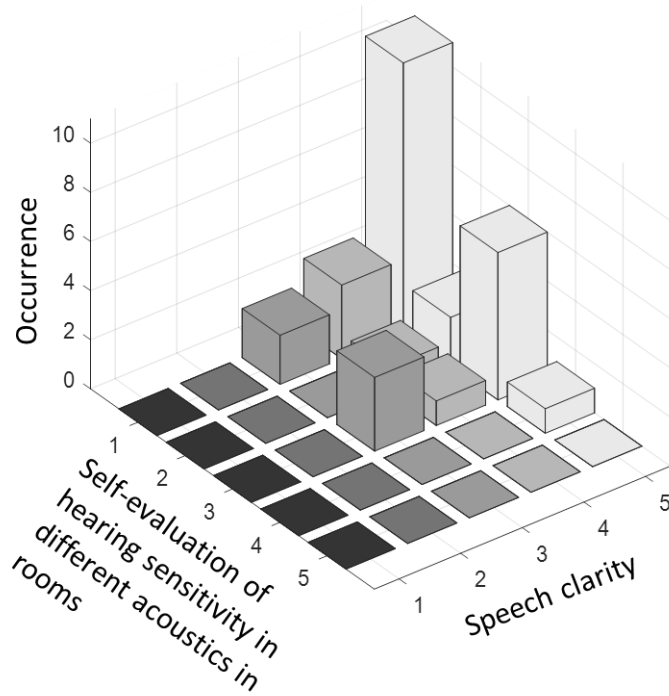


Fig. 8— Counts of subjective speech clarity responses plotted against the self-evaluated sensitivity to acoustic changes and subjective clarity. The self-evaluation scale [5, 4, 3, 2, 1] corresponds to the extent to which an interviewee notices a difference between reverberant and almost anechoic conditions [Always, Frequently, Occasionally, Rarely, Never].