ARCHIVES OF ACOUSTICS
Vol. **46**, No. 2, pp. 229–235 (2021)
DOI: 10.24425/aoa.2021.136578

Research Paper

Relationship Between Chinese Speech Intelligibility of Elderly and Speech Transmission Index

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(*received November 27, 2019; accepted January 11, 2021*)

In this paper, the relationship between Chinese speech intelligibility (CSI) scores of the elderly aged 60–69 and over 70 years old, and speech transmission index (STI) were investigated through the auralization method under different reverberation time and background noise levels (BNL, 40 dBA and 55 dBA). The results show that the CSI scores of the elderly are significantly worse than those of young adults. For the elderly over 70, the CSI scores become much lower than those of young adults. To be able to achieve the same CSI, the elderly, especially those over 70, need much higher STI and greater SNR than the young. The elderly aged 60–69 and over 70 need to improve their STI by 0.419 and 0.058 respectively under BNL 40 dBA, as well as 0.282 and 0.072 respectively under BNL 55 dBA, so as to obtain the same CSI scores as the young adults.

Keywords: speech intelligibility; speech transmission index; signal-to-noise ratio; background noise level; speech sound pressure level; reverberation time.

1. Introduction

As an important parameter for room acoustics, the speech intelligibility is mainly affected by the reverberation time (RT), the speech sound pressure level (SSPL), and the signal-to-noise ratio (SNR). Compared with young adults with normal hearing capacity, most elderly people have difficulties in understanding speech signals in adverse listening environment (Bergman, 1971; Garstecki *et al.*, 1974; Dubno *et al.*, 1984). Nabelek and Robinson (1982) pointed out that the elderly required from 10 to 20 dB higher SSPLs than young adults to obtain a good speech intelligibility scores at different RTs. Harris and Reitz (1985) compared the speech recognition abilities of the normal hearing elderly, hearing impaired elderly, and normal hearing young adults under reverberation and noise conditions. The results showed that the adverse effects of reverberation plus noise on speech recognition increased with age. More specifically, among those with normal hearing, the speech recognition ability of the elderly is significantly lower than that of the young under reverberation and noise conditions. Even in the ideal acoustic environment, the elderly with hearing loss have more difficulties in speech recognition. Helfer and Huntley (1991) studied the method of recognizing English consonants in the presence of reverberation and noise. The subjects were divided into three groups: the elderly with hearing loss, the elderly with mild hearing loss, and the young with normal hearing. The results showed that there were considerable barriers to speech recognition in the elderly under non-ideal auditory environment. A study by Sato (2005) found that older audiences scored 25% lower in speech intelligibility than younger audiences through a series of tests.

Steeneken and Houtgast (1980) considered the influence of interference noise and reverberation and proposed a speech transmission index (STI) to evaluate speech intelligibility in rooms based on modulation transfer function. Tang and Yeung (2004; 2006) found that a strong correlation existed between the RTs and the STIs. The STI can also be estimated according to the RT (Escobar, Morillas, 2015; Nowoswiat, Olechowska, 2016; Leccese *et al.*, 2018). In terms of the effect, early studies on Western languages have shown that STI is highly correlated with the results of speech intelligibility assessment in rooms, and can be used to evaluate and predict speech intelligibility in rooms (Houtgast, Steeneken, 1984). Moreover, the STI method was further improved by Steeneken and Houtgast (1999; 2002a; 2002b). The relationship between STI and subjective speech intelligibility scores for many languages has been established (Houtgast, Steeneken, 1984; Peng *et al.*, 2011; Zhang, Xie, 2012).This index is now used as the objective index for speech intelligibility in rooms by the International Electrotechnical Commission (IEC 60268-16, 2011) and China Standards Committee (GB/T 12060.16, 2017). Peng *et al.* (2011) established the relationship between Chinese speech intelligibility (CSI) and STI of normal hearing adults through a large number of subjective evaluations. However, the elderly are more susceptible to adverse acoustic environments, such as reverberation and noise. Under the same conditions, their speech intelligibility scores are lower than that of younger adults. Thus, the relationship between their speech intelligibility and STI should be different from that of the younger. Zhang *et al.* (2019) used a loudspeaker to reproduce the simulated test signals with different RT in two rooms, and compared the relationship between the CSI scores and STI of the elderly with different age groups. The results showed that CSI score of elderly people increased with STI and was 30% lower than that of young adults averagely under the same acoustical conditions.

In the study of Zhang *et al.* (2019), the SSPL was fixed at 70 dBA with 0, 3, 6, and 9 dB SNR, respectively. Both the SSPL and the background noise level (BNL) were higher than those of daily speech communication situation in rooms. In this paper, the impulse response with different RTs was obtained by room acoustical simulation software. The CSI were respectively evaluated by three groups of participants, who were aged 60–69, over 70, and normal hearing young adults, under two BNLs (40 dBA and 55 dBA) with different SNRs. The aim of this study is to investigate the relationship between CSI scores of the elderly and the STI, to compare the results of different age groups of the elderly and young adults, and to explore the changes in the demand for acoustic environment for the elderly to acquire the same CSI as the young adults with normal hearing.

2. Methods

2.1. Room and sound fields

Many studies have demonstrated that the subjective speech intelligibility evaluation based on the auralization technique is feasible (Peng, 2005; Peng *et al.*, 2011; Siebein *et al.*, 2005; Tyson, 2014; Yang *et al.*, 2006; 2007) and can be easily conducted. In the study, the auralization method is also used for speech intelligibility test for the elderly. In the test, six rooms were modelled according to the size of the real rooms by using ODEON (Christensen, 2009). In each simulated room, a BB93 normal natural source (Christensen, 2009) was set at the front and a receiving position was set in the middle (or back). Certain materials on the room surfaces (room B, C, E, and F) were basically similar with those in the real situations (Peng *et al.*, 2011). For example, in the classroom E, the floor was covered with ceramic tiles. There were large windows on two of the side walls. All other parts of the walls were painted and plastered with brick walls. The ceiling was smooth and painted concrete. In rooms A and D, the sound absorption coefficients of the materials on some surfaces were adjusted (with greater sound absorption coefficient) to obtain the room impulse responses with shorter RTs. A room impulse response from source to the receiving position was obtained in each room model. Six room impulse responses represent six different RT values. The rooms' dimensions, types, shapes, RTs, and STI_{-n}s at the receiver position in each room are shown in Table 1. The STI_{-n} from ODEON excludes the effect of interfering noise.

Table 1. Rooms' dimensions, and RT and STI from the ODEON simulation.

Room	Dimension [m^3]	Type	Shape	RT (500 Hz ~ 1 kHz) [s]	STI_{-n}
A	8.0 × 8.4 × 5.1	Classroom	Rectangle	0.38	0.84
B	19.0 × 18.6 × 5.0	Report hall	Trapezoid	0.61	0.73
C	30.8 × 24.0 × 6.0	Multi-purpose hall	Trapezoid	1.01	0.63
D	16.0 × 8.4 × 5.1	Classroom	Rectangle	1.47	0.53
E	17.6 × 17.6 × 4.7	Classroom	Hexagon	2.15	0.48
F	64.5 × 31.2 × 20.7	Church	Rectangle	5.20	0.36

2.2. Chinese speech intelligibility test

CSI test uses the lists of Chinese rhyme test words specified in GB 4959 (GB 4959, 1985) and SJ2467 (SJ 2467, 1984.). Similar to the modified Rhyme Test of English, there are ten word lists in the test. Each of them contains 25 five-word rows of similar-sounding Chinese monosyllabic words. The 5 words in each row are randomly arranged and differ only in the initial consonant sound (hao, sao, gao, zao, kao). The test words in carrier phrase are "The × row reads ×". All word lists were recorded at a rate of 4.0 words per second and with 65 dBA as sound pressure level, using an omnidirectional microphone with 0.5 m away from a male speaker in an anechoic chamber. An average speech spectrum of the male speaker was used as a criterion for the selection of speech-shaped noise for the test. Because the speech-shaped noise with a frequency spectrum is equivalent to the long-term speech spectrum, the SNR is approximately equal in all the selected frequency bands of speech signal (Steeneken, Houtgast, 1999). The noise and the speech test signal recorded in the anechoic chamber were convoluted with the binaural room impulse response and mixed according to a certain SNR, then reproduced through Sennheiser HD580 headphone under a certain BNL.

2.3. Participants

Eight aged 60–69 and eight aged over 70 people were randomly recruited as paid participants to take part in the experiment. All the participants had the ability to speak in Mandarin. Oral consent was obtained from all participants prior to the start of the study. The pure tone average (PTA) threshold of 60–69 years old group of elderly participants in the frequency range of 500–4000 Hz was given in previous study (Zeng *et al.*, 2020). The PTA threshold of over 70 years old group of elderly participants in the frequency range of 500–4000 Hz is shown in Table 2. The average PTA of over 70 years old group is 36.6 dB HL with standard deviation (SD) of 14.13 dB HL. According to the hearing loss criteria issued by the World Health Organization (WHO) (1997), all 8 elderly people in the 60–69 age group have normal hearing, while in the group of 70s and over, only one subject has normal hearing, five have mild hearing loss, and two have moderate and above hearing loss. To compare with the results from the young adults with normal hearing, 8 young adults (22–25 years old) with normal hearing were recruited to participate in the test. All young adults were undergraduates or graduate students. They spoke standard Mandarin Chinese and had no listening problems. Their PTA values ranged from 5.3 dB HL to 14.5 dB HL, with an average of 10.8 dB HL and a SD of 3.1 dB HL.

Table 2. The results of the pure tone audiometry of the elderly over 70 years old.

No.	Gender	Age	PTA (dB HL)	
			L	R
1	Male	72	43.8	41.8
2	Male	73	17.0	12.8
3	Male	76	36.8	38.5
4	Male	73	37.0	28.0
5	Male	82	52.8	75.3
6	Female	76	31.0	28.5
7	Male	82	31.5	34.8
8	Female	80	38.3	37.5

All participants received instructions a few minutes before a test. The interval between two tests of the same participant was more than 7 days to prevent participants from memorizing the vocabulary. During the test, the subjects were asked to mark one word from five words that they had heard. The CSI score is the average score across 8 participants in each test condition.

2.4. Test conditions

40 dBA and 55 dBA BNL are set corresponding to the noise limit in the living room for the high demand house and the lowest demand noise limit for the dining room in the hotel specified by GB50118 (GB 50118, 2010). In the test, speech-shaped noise was used for background noise. A binaural artificial head MK2B with a detailed torso/shoulders & head was used for the measurement of the 40 dBA and 55 dBA BNL at both ears by adjusting the volume of ROLAND EDIROL UA-25 USB sound card. To avoid the ceiling effect of scoring in the speech intelligibility test, SNRs were set at 0 dBA, 6 dBA, 12 dBA, and −5 dBA, 1 dBA, 7 dBA for 40 dBA and 55 dBA BNL, respectively. However, considering that most of the elderly over 70 years old have hearing loss and need higher SNR, the corresponding SNRs were adjusted at 4 dBA, 10 dBA, 16 dBA and 0 dBA, 6 dBA, 12 dBA, respectively. 42 test conditions included seven different RT (0 s, 0.4 s, 0.6 s, 1.0 s, 1.5 s, 2.2 s, and 5.2 s), two BNLs (40 dBA and 55 dBA), and three SNRs. For each test condition, the STI values were calculated according to the room impulse response, BNL and SSPL (or SNR) at the listening position.

3. Results and discussions

The relationships between CSI scores and STI from three groups of participants under 40 dBA and 55 dBA BNL conditions are shown in Fig. 1. The S-type curve equation was proved to be suitable (Peng

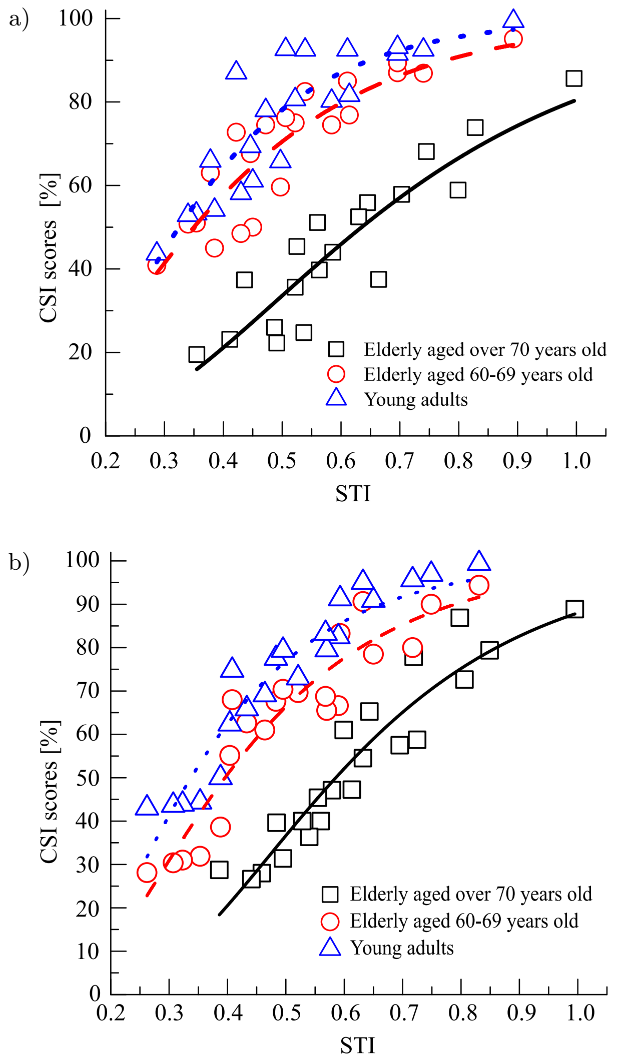

Fig. 1. Relationships between STI and Chinese intelligibility scores: a) 40 dBA BNL, b) 55 dBA BNL.

et al., 2015) and used to fit the relationship between CSI scores and STI

$$\mathrm{SI} = 100 \cdot \left(1 - 10^{-\frac{\mathrm{STI}}{a}}\right)^{b}. \tag{1}$$

The parameters a and b, SDs and coefficient of determination (R^2) obtained from S-type curve Eq. (1) fitting under different age groups and different BNLs conditions are listed in Table 3.

Figure 1 shows that the CSI scores increase with the increase of STI and decrease as age increases. Moreover, the curve slopes gradually decrease, and the growth trends slow down under two BNL conditions. The CSI scores of the two elderly groups are poor comparing to those of young adults, and the scores of the elderly over 70 years old are poorer under the same BNL and STI conditions. When STI approaches 1, it can be concluded from Fig. 1, the maximum CSI of the aged over 70 is about 80% under the condition of 40 dBA BNL, while under the condition of BNL of 55 dBA, the maximum CSI of the aged over 70 is about 90%.

Table 3. Coefficients of S-curve fitting results.

BNL [dBA]	Group	a	b	R^2	SD [%]
	Over 70 years old	0.76	4.41	0.82	8.00
40	60–69 years old	0.56	2.59	0.79	7.49
	Young	0.41	3.89	0.77	8.15
	Over 70 years old	0.59	4.29	0.89	6.61
55	60–69 years old	0.52	2.22	0.88	7.31
	Young	0.43	2.11	0.91	5.86

The higher the score of speech intelligibility, the more speech information the listener can obtain through listening, and the more conducive to communication. For 40 dBA BNL, the highest CSI scores of the elderly over 70 years old is about 80% under no reverberation and 16 dBA SNR condition. In order to compare the STI values required by different age groups to obtain the same speech intelligibility score, the benchmark value was set as 80% CSI score. The corresponding STI values can be obtained from the curves accordingly when CSI score is 80%. Under 40 dBA BNL, for an 80% of the CSI score, the STI needed by young adults is 0.517, whereas it is 0.603 for 60 years olds, and 0.991 for the elderly aged 70 and over. In other words, the STIs needed by participants aged 60 and those over 70 are 0.086 and 0.474 higher than that of young adults, respectively. Under the condition of 55 dBA BNL, for an 80% of the CSI score, the STI needed by young adults is 0.429, while it is 0.527 for the 60s and 0.761 for the elderly aged 70 and over, indicating the differences of 0.098 and 0.332, respectively. When the BNL is different, the difference for STI between the 60–69 years old elderly and the young group under 55 dBA BNL is 0.012 higher than that under 40 dBA BNL, while the difference between over 70 years old elderly and the young under 55 dBA BNL is 0.142 less than that under 40 dBA BNL condition. The results under two BNL conditions show that, compared with the young adults and the elderly aged 60s, the STI of the elderly aged 70 and over needs to be greatly improved to obtain sound speech intelligibility in rooms.

It can be also seen from Fig. 1 that the CSI scores of all age groups under 55 dBA BNL are higher than those under 40 dBA BNL under the same STI condition. Since the SNRs in 40 dBA BNL are higher than those in 55 dBA BNL, the STI values in 40 dBA BNL are greater than those in 55 dBA BNL with corresponding test conditions (i.e. 0 dBA SNR in 40 dBA BNL and −5 dBA SNR in 55 dBA BNL). Moreover, the previous study showed that CSI scores increased rapidly with the increase of SSPL when SSPL was lower than 65 dBA under 50 dBA BNL condition (Peng, 2010). In the present study, most speech sound pressure levels in 55 dBA BNL condition are higher than those in 40 dBA BNL condition. A higher speech sound pressure level helps them to hear the tested word clearly, which leads to relatively high CSI scores, especially for the elderly aged 70 and over with hearing loss.

From Fig. 1, it can be seen that the elderly need a larger STI than young adults to achieve the same CSI scores. Compared with the young, it can be simply assumed that the elderly need higher effective SNR to obtain the same CSI scores as the young adults. One can shift the fitting S-curve of the elderly to the left by a constant A, and the Eq. (1) changes to Eq. (2):

$$\mathrm{SI}' = 100 \cdot \left(1 - 10^{-(\mathrm{STI}-\mathrm{A})/a}\right)^{b}. \tag{2}$$

When the SI′ scores of the elderly from Eq. (2) has maximum correlation coefficient and minimum SD with the SI scores of young adults from Eq. (1), the revised fitting curve of the elderly from Eq. (2) approximately coincides with that of young adults from Eq. (1), and the constant A is obtained. From constant A one can obtain the effective SNR (ΔSNR) that the elderly should be improved.

According to Table 3, there are 4 groups of coefficients a and b in the two groups of elderly under two kinds of BNLs. Each group of a and b of the elderly were substituted into Eq. (2) respectively, and compared with the fitting curves of the young adults, the A values and the improved effective SNR (ΔSNR) are shown in Table 4.

Table 4. A and ΔSNR.

BNL [dBA]	Groups	A	ΔSNR [dBA]
40	Over 70 years old	0.419	12.6
	60–69 years old	0.058	1.7
55	Over 70 years old	0.282	8.5
	60–69 years old	0.072	2.2

Figure 2 shows the relationship between the recalculated CSI scores (SI') from the elderly and the CSI scores from the young adults. It can be seen from the Fig. 2 that all data points are basically distributed near the line $y = x$. The correlation coefficients and SDs are 0.88, 0.88, 0.96, 0.96, 8.27%, 9.98%, 5.92%, and 7.00% under BNL 40 dBA and 55 dBA conditions, respectively. It can be seen from Table 4 that the 60 years olds and those over 70 need to improve the STI by 0.419 and 0.058 respectively to obtain the same CSI scores as the young adults under BNL 40 dBA, as well as improving STI by 0.282 and 0.072 respectively under BNL 55 dBA, which corresponds to improving the SNR by 1.7 dBA & 12.6 dBA and 2.2 dBA & 8.5 dBA, respectively. These results show that the elderly, especially those over the age 70, need much higher STI and greater SNR than young adults to achieve the same

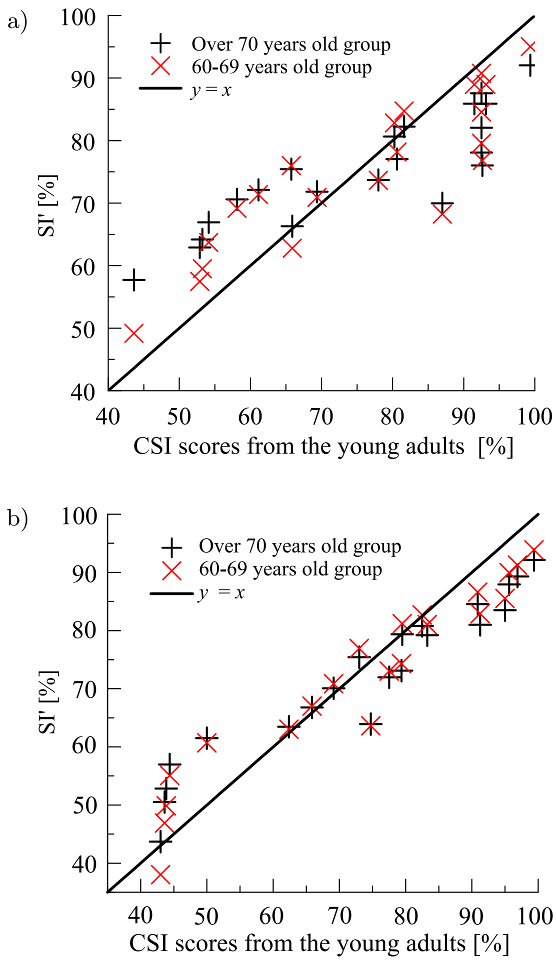

Fig. 2. Relationships between measured Chinese speech intelligibility scores of the young and ones obtained from Eq. (1): a) BNL 40 dBA, b) BNL 55 dBA.

CSI as young adults in rooms. To provide the elderly a good speech communication, some acoustical measures to reduce the BNL and RT, such as sound absorption, noise reduction and sound insulation treatments, should be taken to increase STI and improve SNR in rooms. The architects should pay more attention to the detrimental effect of BNL and RT on the speech communication of the elderly population and provide a good speech intelligibility in rooms for the elderly as far as possible. On the other hand, when communicating with the elderly, one may raise the sound pressure level of their voice to improve SNR.

Zhang *et al.* (2019) also used the fixed SSPL and varied SNR test method to evaluate CSI by 34 elderly aged from 60 to 89. The CSI test was carried out in two real rooms, the SSPL at the position of the receiver was set at about 70dBA. They didn't conduct a PTA threshold test, so the PTA of the subjects was unknown. Figure 3 shows the fitting curve of CSI~STI from Zhang and the present results. As can be seen from Fig. 3, the results of both studies show that the CSI scores of the elderly decreases with age, while

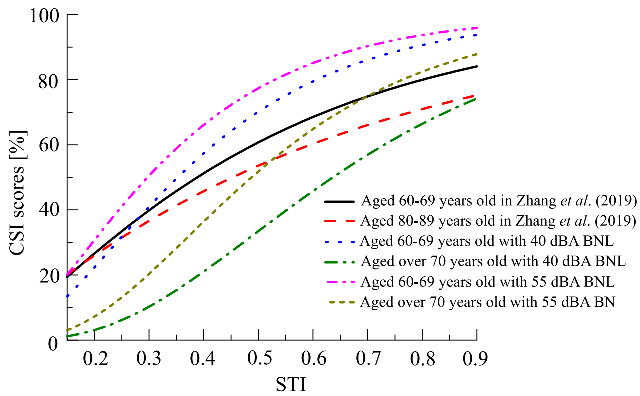

Fig. 3. Comparison with the results of Zhang *et al.* (2019).

the CSI scores increases as the STI rises, but the curve trend is different. Compared with the fixed SSPL test (Zhang's study), the curve slopes for the fixed BNL test are relatively high. In the fixed SSPL test, SNR increases with the increase of STI, but the SSPL remains unchanged. In the fixed BNL test, both SNR and SSPL increase with the increase of STI. From the previous analysis (Peng, 2010), it can be known that both SNR and SSPL have positive effects on the improvement of speech intelligibility of the elderly in the range of sound pressure level. Therefore, the increase rate of speech intelligibility score is higher when both SNR and SSPL are increased than that of only SNR being increased while SSPL remains unchanged. Because the study of Zhang *et al.* (2019) didn't test the PTA threshold of the elderly, the difference in PTA of the elderly may also be the contribution factor for the difference between the present study and that of Zhang *et al.* (2019).

4. Conclusions

In the paper, the relationship between CSI scores of the elderly and STI was investigated by using the auralization method. Subjective CSI test was carried out through three groups of participants aged 60–69 years old, over 70 years old and normal hearing young adults under different room acoustical environments. The relationship between CSI and STI of the elderly was investigated for the aged 60–69 years old and over 70 years old under 40 dBA and 55 dBA BNLs. Under the same BNL condition, even the elderly with normal hearing (60–69 age group in this study), their CSI scores are significantly poor comparing to those of young adults. For the elderly aged 70 and over, the CSI scores become much lower than those of young adults. To achieve the same CSI, the elderly, especially those over the age 70, need much higher STI and greater SNR than young adults. To provide the elderly a good speech communication environment, certain measures should be taken by sound absorption, noise reduction and sound insulation treatment to increase STI and improve SNR in rooms.

Acknowledgements

The authors thank the elderly participants who participated in the experiment. This work is supported by National Natural Science Foundation of China (grant numbers 11674104) and Opening Project of the State Key Laboratory of Subtropical Building Science, South China University of Technology, China (grant numbers 2019ZB18).

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