Increasing speech intelligibility in monaural hearing by adding noise at the other ear

Kang Wang[1, 2, a)], Peng Wang[1], Xiaojun Qiu[2]

[1] Key Laboratory of Modern Acoustics and Institute of Acoustics, Nanjing University, Nanjing 210093, China.

[2] Center for Audio, Acoustics and Vibration, Faculty of Engineering and IT, University of Technology Sydney, Sydney, NSW 2007, Australia

[a)] Author to whom correspondence should be addressed. Electronic mail: 237697663@qq.com.

ABSTRACT

Ambient environment noise can affect speech intelligibility in phone communication. This paper investigates the feasibility of increasing speech intelligibility in monaural hearing by adding noise at the other ear. The testing materials were generated by mixing the speech from the English Coordinate Response Measure corpus with three types of environmental noise, where 4 signals to noise ratios in the speech ear and 14 noise levels in the contralateral ear were included. The experimental results show that a proper level of contralateral noise can improve the speech intelligibility when the signal to noise ratio in the speech ear is lower than a certain level, but a large contralateral noise level has the opposite effect. A preliminary explanation for the phenomena is attempted by using a binaural loudness model and some psychoacoustic and physiological facts.

Keywords: Speech intelligibility; Monaural hearing; Noise; Contralateral

1. Introduction

Ambient environment noise affects the quality of the phone communication where speech is often only presented to just one ear, resulting in poor Speech Intelligibility (SI). SI is defined as the measure of the comprehensible quality of speech, which can be used to quantify the speech perception in monaural hearing with binaural noise [1]. To improve the problem, this paper investigates the effects of contralateral noise on the speech intelligibility in monaural hearing under different Signal to Noise Ratios (SNR).

The perception of the tonal signal presented to one ear was investigated about 70 years ago. In 1948, the masking threshold of a tonal signal for the binaural noise in phase was found lower than that of the noise out of phase [2]. Eight years later, it was found that the tonal signal and noise presented to one ear led to the same masking threshold as these presented to both ears [3]. In 1965, Mulligan and Wilbanks reported that a certain level of correlated noise in the ear without signal improved the detection of a tonal signal in noise, while the uncorrelated noise had the opposite effect [4]. It was confirmed that a given level of the correlated noise in the contralateral ear produced a constant increment in detection independent of the SNR in the signal ear [4]. It was also found that the additional noise to the empty ear could reduce the threshold for the tonal signal presented only to one ear mixed with noise [5-7].

Many studies have been conducted on the perception of speech to evaluate the effects of broadband noise. In 1943, white noise presented to one ear was found to be able to improve the loudness of speech in the opposite ear [8]. Two years later, Egan reported that a sufficiently intense noise in one ear would mask speech heard in the contralateral ear while a weaker noise has the opposite effect of enhancing the loudness of speech [9]. They also noticed a move of the localization of speech to the center of the head when noise was introduced into the opposite ear due to the effect of the noise on the muscles of the contralateral middle ear.

There have been many studies that use SI to describe the noise and aging effects on speech communication. In 2005, the effects of multi-talker babble and speech shaped noise on the intelligibility of vowel and consonant were discussed, which revealed that the multi-talker babble noise had worse effects than the speech shaped noise when the SNR is low [10]. Five years later, Li *et al*. predicted the intelligibility of individual consonants in noise for hearing-impaired listeners, which was also a syllable-based investigation [11]. In 2011, the acceptable range of speech level was investigated on the basis of word intelligibility scores as a function of background noise level [12]. The SI of young adults were found larger than that of the elderly persons (the subjects in this paper were chosen between 20 to 22 years old, making the effects of age indistinctive). More recently, the effects of the reverberation and noise level on the SI were investigated, where a complex interaction between the noise characteristics and reverberation was found by observing the SI scores [13]. These SI based studies were under binaural speech and did not consider the effects of the contralateral noise on monaural speech, which is the objective of this paper.

The reasons for the speech improvement generated by the contralateral noise have been explored from the physiological aspects. The Medial Olivocochlear Bundle (MOCB) was found playing an important role on the improvement of detecting speech under ambient noise caused by the contralateral noise, which was also verified by the animal experiments [14-16]. More detailed results show that the MOCB reduces the effects of the noise on the speech detecting and increases the SNR for the target signals [17-19]. Kawase and Liberman reported that the activation of MOCB suppressed the response of auditory fibers to the masking noise [20]. This reduces the adaptation of fibers to noise, resulting in the increase of the response of auditory fibers to target signals indirectly.

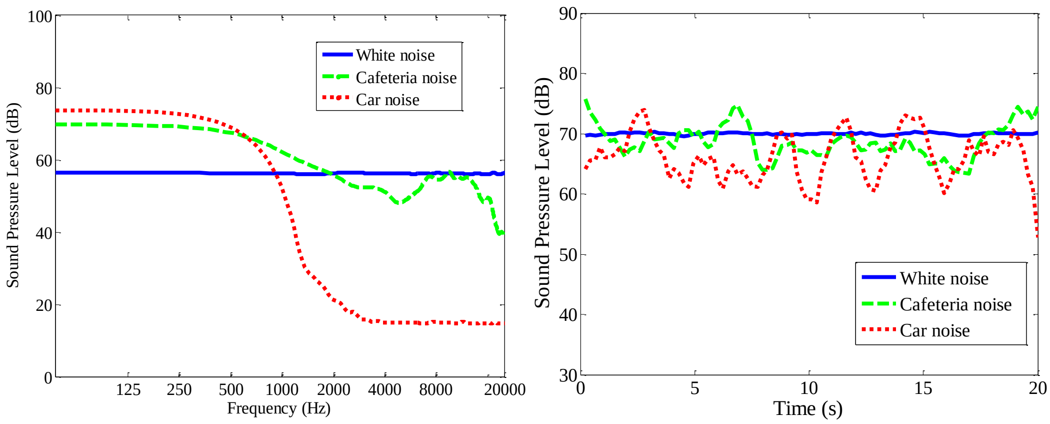
The speech intelligibility during the phone communication is directly affected by the ambient environment noise, especially for people who communicate with their second language. The present paper explores the effects of the contralateral noise on speech intelligibility in monaural hearing. In this research, the Sound Pressure Level (SPL) of the speech is fixed at 70 dB, which is typical in the communication. The speech signal with different SNR is presented to speech ear while three kinds of noise (from 64 dB to 90 dB) are presented to the contralateral ear, where the SIs are measured to show the effects of the contralateral noise. The discoveries from the research are useful for developing new methods to help people to increase phone communication quality under noisy environments.

2. Methodology

2.1. Testing materials

The speeches used in the test are from the CRM corpus, which has been widely used in psychoacoustics research [21]. The CRM corpus consists of 256 short sentences with different combinations of 8 signals (Charlie, Ringo, Laker, Hopper, Arrow, Tiger, Eagle, Baron), 4 colors (Blue, Green, Red, White) and 8 numbers from 1 to 8. All the sentences share the same structure: "ready (a signal) go to (a color) (a number)". These sentences were spoken by 8 native English speakers (4 males and 4 females) and recorded in an anechoic chamber.

Three types of noise were used in the test, which were white noise, cafeteria noise and car noise. The white noise was generated with *Adobe Audition* software, while the cafeteria noise and car noise were taken from the ETSI EG 202 396-1, where the cafeteria noise was recorded in a busy cafe and the car noise was recorded in a midsize car at the speed of 100 km/h [22]. Figure 1 (a) shows the spectrum of the three types of noise at the same SPL by using the Welch processing method. The spectrum is flat in the whole frequency range for the white noise, while the energy is dominated under 2000 Hz for the cafeteria noise and under 1000 Hz (especially under 400 Hz) for the car noise. Fig. 1 (b) shows the SPL in time domain for the 3 types of noise (only 20 s used in the test are shown). The value of statistical levels L_{10} and L_{90} are approximate 70.2 dB and 70.0 dB for the white noise, 73.8 dB and 66.5 dB for the cafeteria noise, and 72.2 dB and 68.2 dB for the car noise. More details about the properties of the cafeteria noise and the car noise are available online at: http://portal.etsi.org/docbox/STQ/Open/, which is under the folder named “EG 202 396-1 Background noise database” [22].



(a) (b)

FIG. 1. (Color online) (a) The spectra and (b) the SPL in time domain for the white noise, cafeteria noise and car noise used in the experiments.

The SPL of the speech and the noise were calibrated by using a B&K Head and Torso Simulator (HATS, Type: 4128c), where the sound material was played back via professional headphones (Type: AKG K702, sensitivity: 105 dB/V) on the HATS. Figure 2 shows the procedure for making the mixed audio. The speech signal randomly chosen from the CRM corpus mixed with noise was presented to the speech ear (right ear) and the noise signal was presented to the contralateral ear (left ear). This is because the right ear is often chosen to receive the call in phone communication.

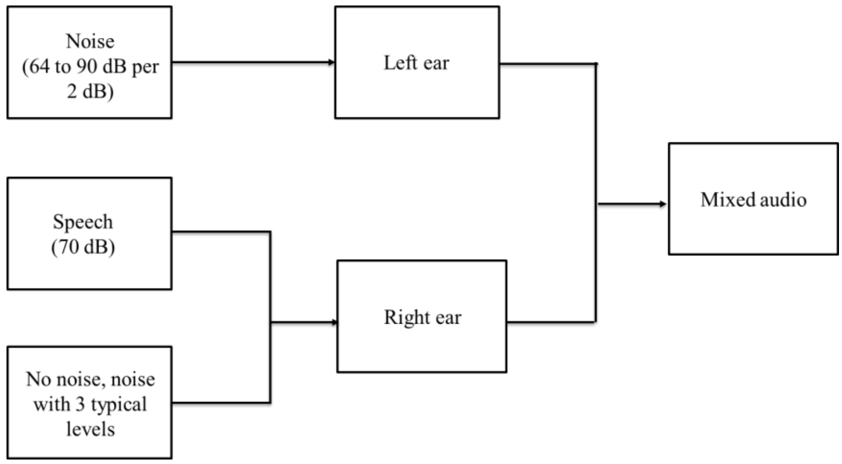


FIG. 2. The procedure for making the mixed audio for the test.

The SPL of the speech sentence was fixed at 70 dB, which is the normal value in phone communication [23]. Forty-two randomly shuffled groups of the materials were used in the test with combinations of 14 noise level (from 64 to 90 dB with a step of 2 dB) at the contralateral ear and the clean signal (speech without noise), noise signal with 3 SNRs (–6 dB, –10 dB and –14 dB for the white noise and –8 dB, –12 dB and –16 dB for the cafeteria noise and car noise) at the speech ear. The mean A-weighted SPLs are 67.6 dB, 71.0 dB, 69.3 dB, and 56.4 dB as A-weighted for the speech, white noise, cafeteria noise and car noise at 70 dB (SPL, not weighted), respectively. The mean SNRs in A-weighted values corresponding to SNR = –6 dB, –10 dB, –14 dB (not weighted) are –9.4 dB, –13.4 dB, –17.4 dB for the white noise, are –9.7 dB, –13.7 dB, –17.7 dB for the cafeteria noise with SNR = –8 dB, –12 dB, –16 dB (not weighted), and are 3.2 dB, –0.8 dB, –4.8 dB for the corresponding car noise.

The structure of the testing material is shown in Fig. 3, where two listening sections were designed in one test and each section has 21 groups which each consisted of 10 audios. The 2-seconds noise excerpts inside a group are different, but all groups use the same excerpts to make the results comparable. A 5-minute break was inserted between the 2 listening sections, when nothing was played back so that the subjects could have a rest. There was no break between 2 adjacent groups. Each mixed audio was played at the first 2 seconds, and then there was a 4-second break between the 2 adjacent audios so that the subjects could choose the answer based on what they had heard.

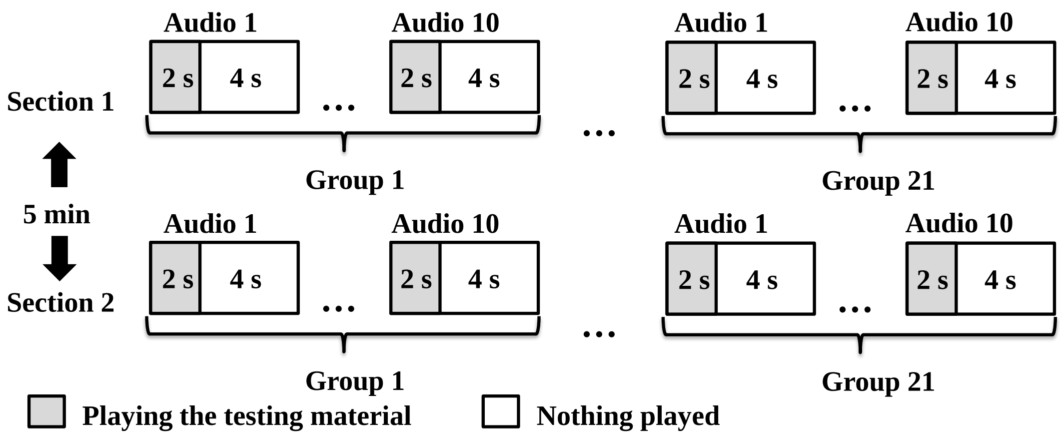


FIG. 3. The structure of the testing materials.

2.2. Procedure

Thirty six normal-hearing volunteers (18 females, 18 males, aged between 20 and 22 years old) from Nanjing University participated in the listening test. All the subjects have passed the College English Test Band 6, ensuring that they have no trouble in recognizing the target words. They were randomly divided into 3 groups (6 females and 6 males) corresponding to 3 types of noise.

The testing material was played back with the headphones. The listening tests were performed in the sound insulation chamber of Nanjing University, which has a background noise lower than 40 dB as A-weighted value. Before the tests, all subjects were informed of the structure of the sentences and all possible answers. To help them to be familiar with the testing procedure, they were asked to listen to a 3-minutes pre-test section, which is the same as the formal test section but without noise. Each section lasted 21 minutes in the formal tests and there was a 5 minutes break between the two sections, so one whole test lasted 47 minutes for one subject.

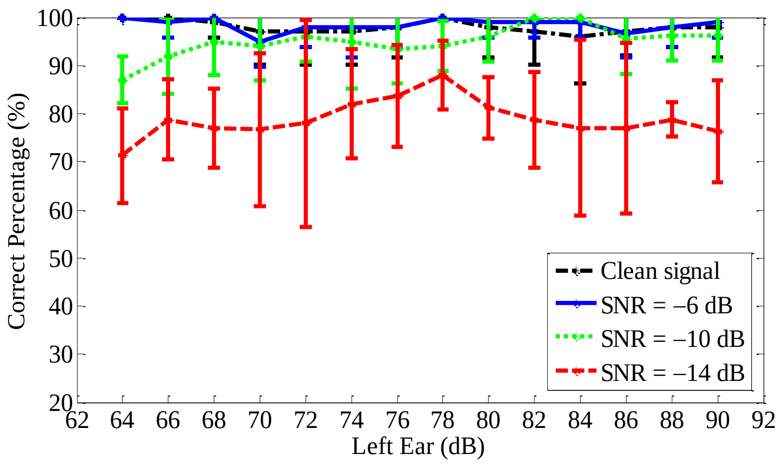
After all the volunteers completed the test, the answer sheets were collected and graded. The SI was obtained by calculating the percentage of the sentences that have all three target words correct. If the differential between the correct percentage of one subject and the mean correct percentage of all subjects is larger than 3 times of the standard deviation, the data needs to be rejected [24]. According to this standard, the abnormal data was removed first, and the results of 10 qualified subjects (5 females, 5 males) for each type of noise were used for data analysis in the next section.

3. Data analysis and discussion

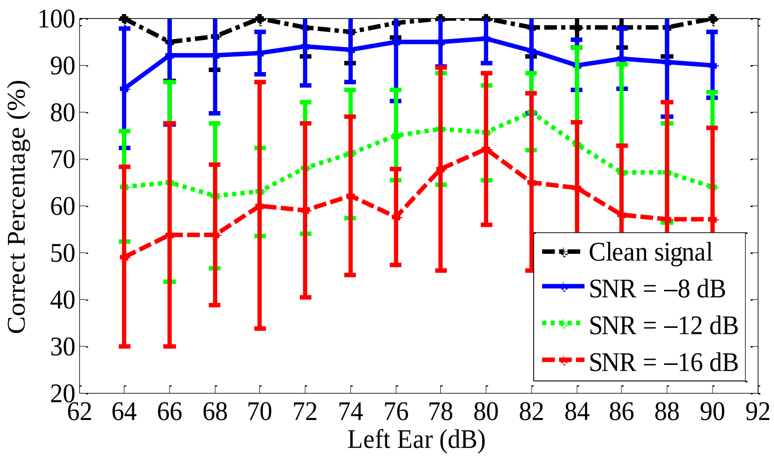
3.1. Data analysis

For the white noise, the 3 typical SNRs in the speech ear were selected as −6 dB, −10 dB and −14 dB to let the noise have significant effect. The cafeteria noise, coming from background speech from many customers, cup impact and coffee machines, is not as stable in time domain as the white noise, while the sound power of the car noise is mainly at the frequencies lower than 1000 Hz, especially lower than

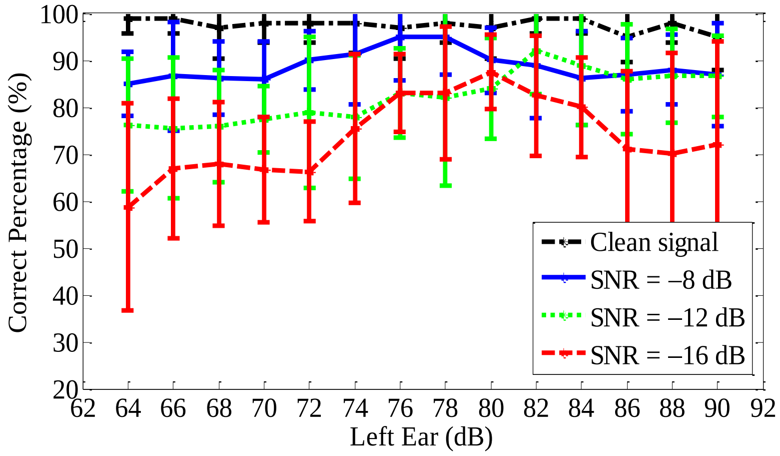
400 Hz. According to a pretest of 4 subjects, the contralateral noise level has no significant effect on the SI for SNR larger than −10 dB for the cafeteria noise and car noise. So the 3 typical SNRs at the speech ear for the cafeteria and car noise were selected as −8 dB, −12 dB, and −16 dB to make the effects obvious, which were 2 dB lower than that for the white noise. Figure 4 shows the mean intelligibilities and mean-square deviations for 10 listeners under different noise levels presented to both ears. The black dashed and dotted line, the blue solid line, the green dotted line and the red dashed line represent that for the clean signal and the noise signals with 3 typical SNRs, respectively.



(a)



(b)



(c)

FIG. 4. (Color online) The mean intelligibilities and mean-square deviations of 10 listeners as a function of noise level at the contralateral ear for (a) white noise, (b) cafeteria noise, and (c) car noise.

For the results of the white noise shown in Fig. 4(a), when there is no noise at the speech ear, the correct percentages are in range of 98 ± 2% and the effect of contralateral noise is not significant (p > 0.05). Here, p value is the product of one-way analysis of variance, and the statistical findings are considered significant for p value lower than 0.05 [23]. When the SNR at the speech ear is –6 dB, the correct percentages are in range of 97 ± 2% and the effect of contralateral noise is still not significant (p > 0.05). But when the SNR decreases to –10 dB, the correct percentage rises at first and reaches 100% when the contralateral noise levels are 82 dB and 84 dB, while falls to 95% when the noise level is 86 dB, and approaches a constant at 96% when the noise level becomes higher. Similar trend has been found when the SNR at the speech ear is –14 dB. The correct percentage reaches 88% at 78 dB and falls to 77% at 84 dB, and then approaches a constant at 77%. The effect of the contralateral noise is significant ($p < 0.05$) when the SNRs are −10 dB and −14 dB at the speech ear.

For the results of the cafeteria noise and car noise shown in Figs. 4(b) and (c), when there is no noise at the speech ear, the effect of the noise level at the contralateral ear is not significant ($p > 0.05$). When the SNR at the speech ear is −8 dB, the correct percentage increases at some certain contralateral noise level, but the effect of the contralateral noise is still not significant ($p > 0.05$). When the SNR decreases to −12 dB, the correct percentage rises at first and reaches the maximum when the noise levels are 82 dB, while falls to a local minimum when the noise level is 86 dB, and then approaches a constant when the noise level becomes higher. The same trend has been found when the SNR at the speech ear is −16 dB. The correct percentage reaches the maximum at 80 dB and falls to a local minimum at about 86 dB, and then approaches a constant. The effect of contralateral noise was significant ($p < 0.05$) when the SNRs are −12 dB and −16 dB at the speech ear.

Figure 4 also shows that the SNR at the speech ear is the major factor for the SI. For a lower SNR noise at the speech ear, SI is often poor. For example, the mean correct percentage is about 79% for the white noise with a SNR of −14 dB, while are about 60% and 74% for the cafeteria and car noise with a SNR of −16 dB, respectively. However, by increasing the noise level on the speech ear, the mean correct percentage can be increased to 97%, 81% and 86%, respectively. In the figures, the correct percentage at a contralateral noise level of 90 dB is not generally lower than that at 64 dB, indicating that a high contralateral noise can increase the SI under some conditions as discovered in this research.

3.2. Discussion

For all the three types of noise, the contralateral noise has no significant effect on the SI when the SNR at the speech ear is greater than a certain value (–6 dB for the white noise, –8 dB for the cafeteria and the car noise). When the SNR at the speech ear is lower than –10 dB for the white noise and –12 dB for the other two types of noise, the SI rises to the maximum when the contralateral noise level is at about 80 dB, falls to the bottom at about 86 dB, and then approaches a constant with larger noise level. It is clear that a proper increase of the contralateral noise level improves the SI, and the most suitable noise level is about 80 dB, which is about 10 dB higher than the speech level. The SI with a high contralateral noise level can be larger than that with a low contralateral noise level. The effect of the SI enhancement from the contralateral noise is more significant when the SNR is lower in the speech ear.

In the binaural loudness model developed by Moore and Glasberg [25], S_L and S_R denote the specific loudness at the left and right ears respectively, which can be obtained by using the Loudness_ANSI_S34_2007 program [26]. It is assumed that there are inhibitory interactions between the two ears, such that a signal at the left ear inhibits (reduces) the loudness evoked by a signal at the right ear, and vice versa. L_L and L_R are the loudness at the left and right ears that are reduced by the contralateral ear, which can be calculated by using Eqs. (1) and (2):

$$L_{\mathrm{L}} = S_{\mathrm{L}} / B_{\mathrm{L}} \quad (1)$$

$$L_{\mathrm{R}} = S_{\mathrm{R}} / B_{\mathrm{R}} \quad (2)$$

where B_{L} and B_{R} are the factors representing the effects from the contralateral ear, which reveals the inhibition interactions between the two ears and can be modeled with Eqs. (3) and (4) [25],

$$B_{\mathrm{L}} = 2/[1+\{\mathrm{sech}(S_{\mathrm{R,a}} / S_{\mathrm{L,a}})\}^{q}] \quad (3)$$

$$B_{\mathrm{R}} = 2/[1+\{\mathrm{sech}(S_{\mathrm{L,a}} / S_{\mathrm{R,a}})\}^{q}] \quad (4)$$

where q is a constant (q = 1.5978), $S_{\mathrm{L,a}}$ and $S_{\mathrm{R,a}}$ are the weighted moving averages of S_{L} and S_{R} respectively [25]. The moving averages are implemented by using a convolution with a Gaussian function described in [25] for the broadband tuning of the inhibition. Eqs. (1) and (2) show that a larger B_{L} (B_{R}) leads to a lower L_{L} (L_{R}) in the corresponding ear.

Assuming to use the right ear as an example, the values of B_{R} as a function of $S_{\mathrm{L,a}}/S_{\mathrm{R,a}}$ (the ratio of the averaged loudness at the left ear to that at the right ear) are shown in Fig. 5, where it shows that a larger averaged loudness in the contralateral ear ($S_{\mathrm{L,a}}$) leads to a larger B_{R}, so L_{R} (the loudness at the right ear that is reduced by the contralateral ear) becomes smaller. In this study, the proper level of noise presented to the contralateral ear (left ear) decreases the loudness of noise at the speech ear (right ear), resulting in a higher SNR and SI. When the ratio of the averaged loudness at the left ear to that at the right ear tends to infinite, B_{R} tends to 2, indicating that the reduction of the loudness at the right ear is limited by a factor of 2. This implies that the loudness reduction effect caused by the contralateral signal is limited to a certain level and cannot be infinitely large.

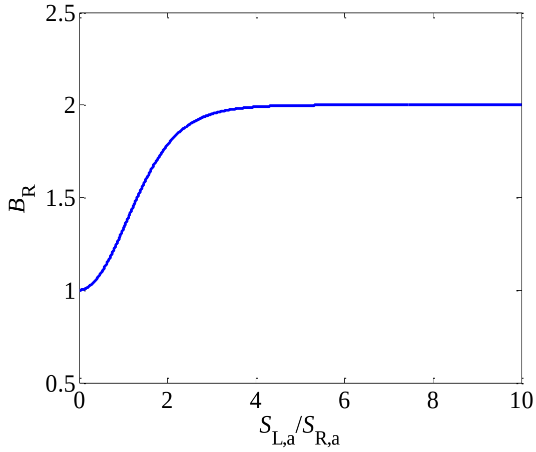


FIG. 5. (Color online) The curve of the effective factor at the right ear (B_R) as a function of the ratio of the averaged loudness at the left ear to that at the right ear ($S_{L,a}/S_{R,a}$).

Figure 6(a) shows the loudness of the three types of noise at different noise level, which was calculated by using the Loudness_ANSI_S34_2007 program [26]. Denote R_R as the loudness reduction in the right ear generated by the contralateral noise and ΔR_R as the increment of loudness reduction at different contralateral noise level, which can be calculated with Eq. (5) and (6),

$$R_R = S_R - L_R \tag{5}$$

$$\Delta R_{R,i} = R_{R,i} - R_{R,i-2} \tag{6}$$

where i = 66, 68, …, 90 is an index for the noise level in the contralateral ear from 64 to 90 dB with a step of 2 dB. Figs. 6(b-d) show the loudness reduction (R_R) and the increment of loudness reduction (ΔR_R) of the noise at the speech ear produced by the contralateral noise, respectively. The R_R increases when the contralateral noise level becomes larger, but ΔR_R turns to decrease after a certain value. When the contralateral noise level is low, the small R_R cannot make a large improvement on the SI, but when the noise level is too high, the ΔR_R turns to be limited, which may not compensate the effects of more noise. This might be the reason that the highest SI happens at the contralateral noise level of about 80 dB. The quantized relationships among the SI, R_R and other factors such as the SPL of the speech are complicated, which need further investigations in future.

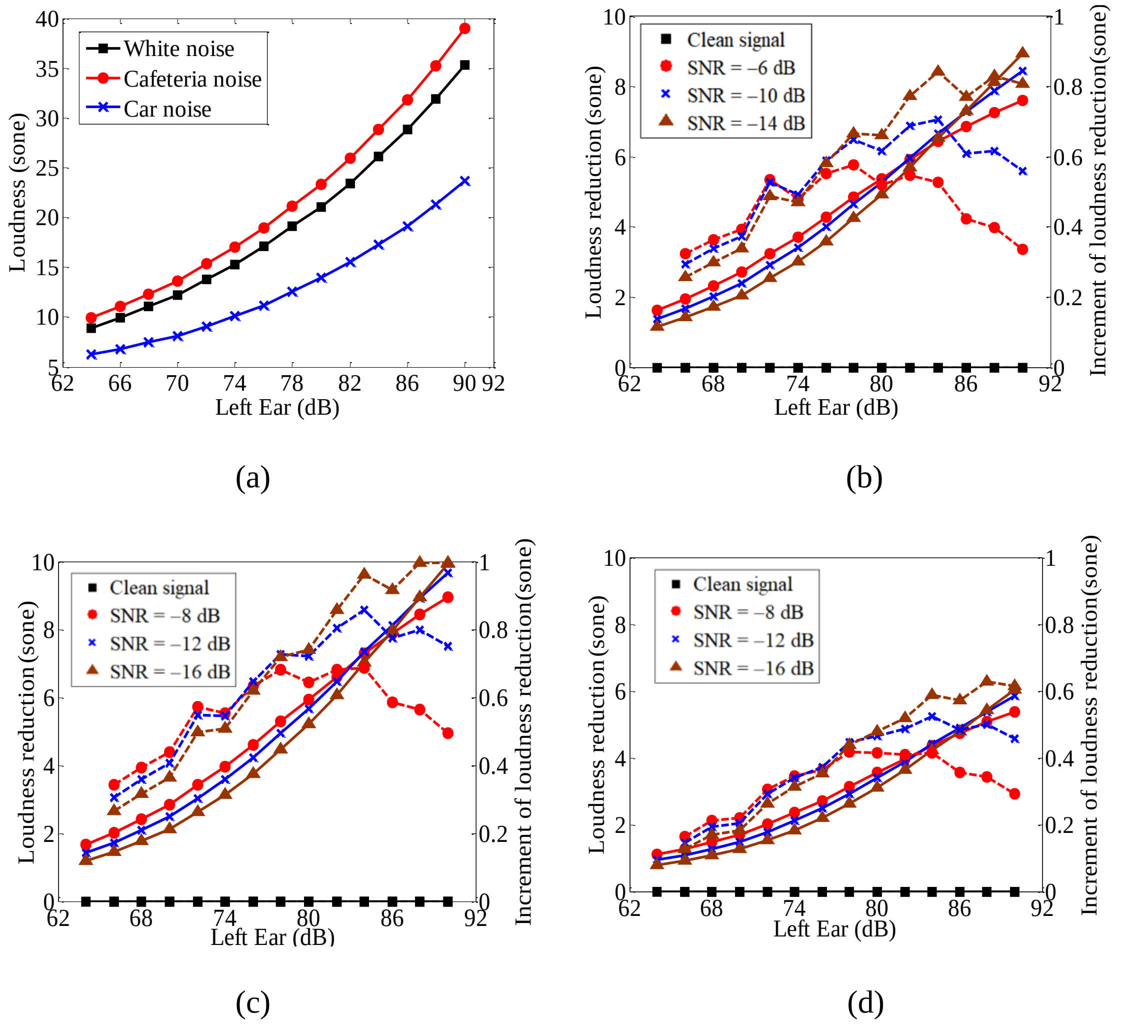


FIG. 6. (Color online) (a) The loudness of the three types of noise at different noise level, the loudness reduction (solid lines) and the increment of loudness reduction (dash lines) of the noise at the speech ear produced by the contralateral noise for (b) the white noise, (c) the cafeteria noise and (d) the car noise.

In the physiological research, the Medial Olivocochlear Bundle (MOCB) was found playing an important role on the improvement of detecting speech under ambient noise [14-18]. The function of Olivocochlear Bundle (OCB) can be tested by the suppression of Otoacoustic Emissions (OAE) of contralateral ear [27]. Giraud *et al*. claimed that the OCB improved the detection of speech only with the noise presented to the ipsilateral ear [28]. Kumar and Vanaja explored the correlation between the speech detection and the suppression of OAE and found that the OCB improved the speech detection by suppression the ambient noise [29]. The reduction of the SI resulted from the contralateral noise in their work is nearly 1% for the cases with the clean signal and the noise signals with SNR = 20 dB at the speech ear, but is nearly 10% when SNR is 10 and 15 dB, which is consistent with the Giraud's results. These results support the facts that the enhancement of the SI from the contralateral noise is large when the SNR at the speech ear is low and the SI is not affected by the contralateral noise when the SNR is high.

4. Conclusions

A speech intelligibility test has been conducted with 36 students to investigate the effects of contralateral noise on the speech intelligibility that was only presented to one ear under different signal to noise ratios. It is found that a suitable level of contralateral noise can improve the speech intelligibility while a contralateral noise level larger than a certain value decreases the speech intelligibility. The enhancement of speech intelligibility from the contralateral noise will be larger for lower SNR at the speech ear. It is also found that the contralateral noise has no significant effect on the speech intelligibility when the signal to noise ratio at the speech ear is larger than a certain value. A preliminary explanation for the phenomena is attempted by using a binaural loudness model and some psychoacoustic and physiological facts. Future work includes the way of controlling the contralateral noise level and the speech intelligibility under more general situations, such as multiple speech levels at the speech ear and different types of noise in both left and right ears.

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