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ORIGINAL ARTICLE

Preliminary Measurements of Binaural Masking-Level Difference When Using Hearing Aids for Sensorineural Hearing Loss

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Abstract The Binaural Masking-Level Difference phenomenon occurs both in listeners with normal hearing and with sensorineural hearing loss (SNHL). Previous studies of BMLDs involving SNHL listeners used a 500- or 2000-Hz pure tone as the target signal, but the BMLD performance of SNHL listeners with stimulus amplified for other frequencies has not been reported previously. Therefore, this study aimed to measure the BMLD in SNHL listeners at various frequencies after amplification by hearing aids. Thirty subjects with mild to moderately severe SNHL participated in the experiments. The BMLDs were measured based on the detection threshold differences for pure tones of 125, 250, 500, 1000, and 2000 Hz in the presence of white noise when presented interaurally in phase (S_0N_0) and interaurally in antiphase ($S_\pi N_0$). The results show that when using white noise as a masker, the average detection thresholds for the target signals were significantly lower in the $S_\pi N_0$ condition compared to those in the S_0N_0 condition ($p < 0.001$). The SNHL subjects had mean BMLDs of 2.3, 4.8, 4.7, 4.2, and 3.7 dB at 125, 250, 500, 1000, and 2000 Hz, respectively. The results obtained in the present study provide preliminary support that SNHL listeners hear target signals easier in noisy environments when the signals are amplified by hearing aids and presented in antiphase.

Keywords Binaural masking-level difference (BMLD) · Sensorineural hearing loss (SNHL) · Hearing aids

1 Introduction

Binaural hearing plays an important role in enhancing the ability to detect signals in noisy environments, which can be illustrated in laboratory studies by measuring the binaural masking-level difference (BMLD) [1]. BMLD refers to the difference in the just-audible test-tone level if the interaural phase difference of the signals presented to the two ears differs from that of the masker, which results in listeners hearing the target signal at a lower volume in the presence of noise. Previous studies have revealed that the BMLD is dominant when the target signals are interaurally in antiphase [1–3]; that is, the listener can hear target signals at a lower volume in noisy environments when the signals are presented at the two ears in antiphase.

The BMLD phenomenon is known to occur both in normal-hearing listeners [2, 3] and in listeners with sensorineural hearing loss (SNHL) [4, 5]. Previous studies on the BMLD in SNHL listeners have only used a 500- or a 2000-Hz pure tone as the target signal [4–6]. Quaranta and Cervellera used a 500-Hz pure tone as the target signal and a broadband noise as the masker at 60 dB sensation level to measure the BMLD in eight SNHL listeners with the audiogram sloping from 2000 to 8000 Hz; the threshold at 500 Hz was asymmetric within 10 dB [4]. Jerger et al. used a 500-Hz pure tone as the target signal and a 80-dB sound

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pressure level (SPL) wideband noise as the masker to measure the BMLD in 45 mild to moderate SNHL listeners [5]. The BMLD obtained in Quaranta and Cervellera's study was 5.7 dB and those obtained in Jerger et al.'s study decreased with increasing hearing loss level. Jerger et al.'s study suggests that using a fixed-level masker could be viewed as a fixed-level amplified stimulus, which may lead to an underestimation of the BMLD of moderate-hearing-loss listeners. Hall and Harvey also suggested that the level of stimulus should be as high as comfort permits when measuring the BMLD in clinical-hearing-loss listeners [6]. Therefore, when measuring the BMLD of hearing-loss listeners, amplification may be required.

Reduced intelligibility of speech in the presence of noise is an almost universal complaint from SNHL listeners who wear hearing aids [7–9]. Wireless technologies make it possible to exchange real-time information between bilateral hearing aids [10–12], which makes it possible to manipulate the phases of the signals supplied to the two hearing aids (e.g., to produce the antiphasic condition) so as to generate a stronger binaural hearing response, and may improve the listening performance of hearing aid wearers in noisy conditions. The BMLD performance of SNHL listeners with amplified stimulus at other frequencies has not been reported. Wide-dynamic-range compression is one of the common amplification schemes of commercial hearing aids. The compression amplification mechanism is used to protect the listener's residual hearing from signals that reach uncomfortable levels. Therefore, this study aimed to measure the BMLD in SNHL listeners at various frequencies after amplification using hearing aids. The results of this study may provide information for supporting further binaural applications of bilateral hearing aids.

2 Materials and Methods

2.1 Subjects

The research experiments involving human subjects were reviewed and approved by the Institutional Review Board (IRB) of Tri-Service General Hospital, Taiwan (IRB No. TSGHIRB: 2-102-05-137). All participating subjects provided both oral and written informed consent. Thirty subjects, according their degree of hearing loss, were stratified into three groups: mild (nine subjects, six females and three males, aged 61.6 ± 15.2 years, mean ± standard deviation), moderate (11 subjects, five females and six males, aged 72.3 ± 10.4 years), and moderately severe (ten subjects, four females and six males, aged 59.5 ± 24.2 years). The following criteria were applied when selecting SNHL subjects: (1) a pure-tone threshold average of greater than 25 dB hearing level (HL) [13, 14] (2) a deviation in the SNHL between the two ears of no more than 15 dB over the investigated frequency range, since an asymmetric loss would seriously affect the BMLD [5], and (3) normal middle-ear function, in order to exclude subjects with conductive hearing loss. Figure 1 shows the audiograms of all subjects grouped by degree of hearing loss.

2.2 Experimental Setup

Figure 2 shows the experimental setup. The masker and target signals were generated by a clinical audiometer (Interacoustics AC40, Middelfart, Denmark). The target signals were pure tones of 125, 250, 500, 1000, and 2000 Hz, which were delivered from channel 1 of the audiometer. Frequencies of 500, 1000, and 2000 Hz were chosen as the target signals since they are considered to be the most important for speech intelligibility [15]. For SNHL subjects who speak Chinese, a special acoustical feature (the fundamental frequency (f_0) for the perception of Mandarin tones) ranges from 125 to 250 Hz [16, 17]. The present study aimed to measure the BMLD in SNHL subjects with two hearing aids and to determine whether this method provides information for supporting further binaural applications of bilateral hearing aids. Therefore, the BMLD was measured at frequencies of 125, 250, 500, 1000, and 2000 Hz. The masker was white noise delivered from channel 2 of the audiometer. To compensate for the reduced hearing of the SNHL subjects, the white noise and pure tone were individually fed into a pair of sound chambers and amplified by two hearing aids (Aescu FOCUS 8 M, Taipei, Taiwan) therein. The sound chambers were designed by our laboratory, and their phase and frequency responses were validated by IEA Electro-Acoustic Technology Co., Ltd, Taipei, Taiwan.

The white noise or pure tone was played inside each chamber through a loudspeaker. The hearing aids in the chambers were fitted with the default target gains of the NAL-NL1 formula based on the audiogram of the participating subject. The amplified white noise or the amplified pure tone produced by the hearing aids were received by artificial ears, comprising externally polarized ear simulators (G.R.A.S. RA0045) and an ear-mould simulator (G.R.A.S. KB0110), according to IEC60318-4. The artificial ears then passed the amplified signals to circuitry comprising an inverter and two adders. The phase of the amplified pure tone could be manipulated as in phase (S_0) or in antiphase (S_π), and the amplified pure tones then were combined with the amplified white noise to produce S_0N_0 and $S_\pi N_0$ signals. A previous study revealed that the BMLD is dominant when the target signals are interaurally in antiphase [2], so the phases of the target signals were made interaural antiphasic before being delivered to the

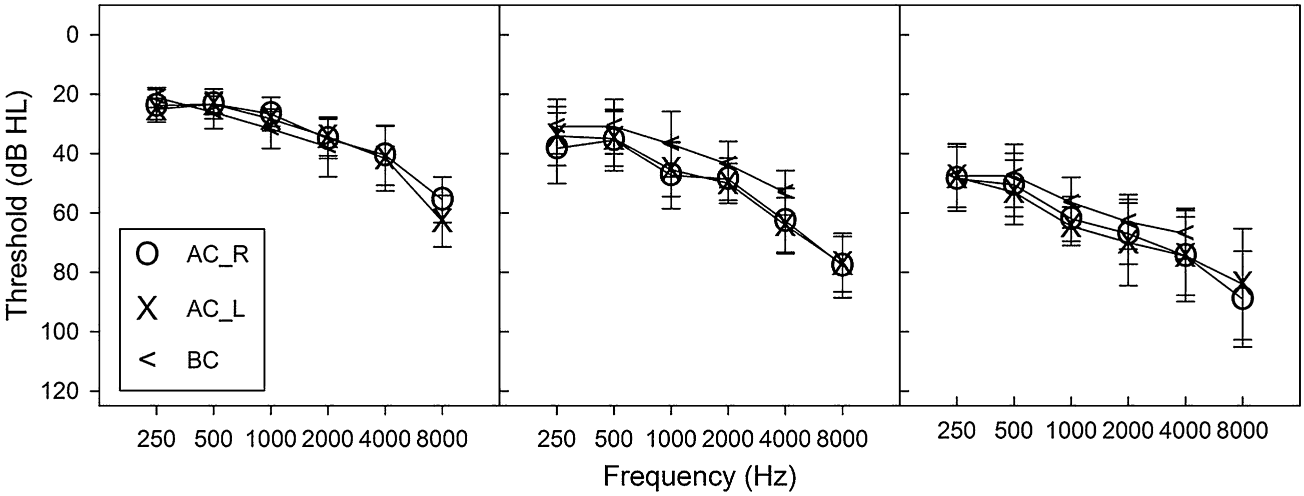

Fig. 1 Audiograms of mild (*left*), moderate (*middle*), moderately severe (*right*) hearing loss subjects. *Circles* ("O") and *crosses* ("X") indicate thresholds of right ear (AC_R) and left ear (AC_L), respectively, for air-conducted tones, and *left angle brackets* ("<") indicate thresholds for bone-conducted (BC) tones

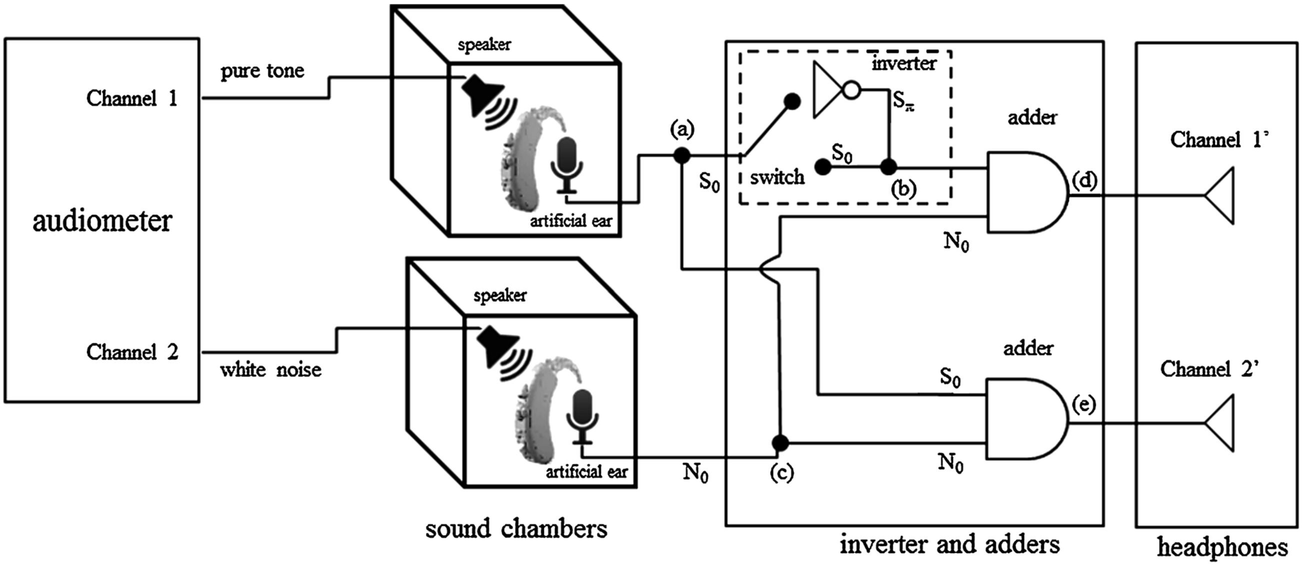

Fig. 2 Experimental setup. Nodes: (*a*) input to inverter (*b*) output from inverter (*c*) in-phase noise (N_0) supplied to two adders, and (*d*) and (*e*) outputs of the adders to channel 1' and channel 2', respectively

SNHL subjects via headphones (TDH-39P). Figure 3 shows a schematic diagram of the S_0N_0 and $S_\pi N_0$ test conditions.

The precisions of the phase inversion function of the inverter (indicated by the dashed rectangle in Fig. 2) and the adders were measured using an electrical and acoustical measurement system (CLIO 10 version 10.31, Audiomatica, Firenze, Italy). A 1-V tone test signal swept from 20 to 8000 Hz in 1/12 octave bands was input to node (a) in Fig. 2 while node (c) was kept floating (no signal input). The phase response was recorded as the phase of the output relative to the input. Two phase responses were measured, that between nodes (d) and (a) and that between nodes (e) and (a), and the differences between these two phase responses were calculated.

2.3 Procedure

The experiments were conducted in the Department of Otolaryngology-Head and Neck Surgery of Tri-Service General Hospital, Taipei, Taiwan. Audiometric data required for the experiments were obtained by conducting hearing assessments of the subjects. The hearing assessment included a tympanograph to evaluate middle-ear function and a pure-tone audiogram to quantify their SNHL.

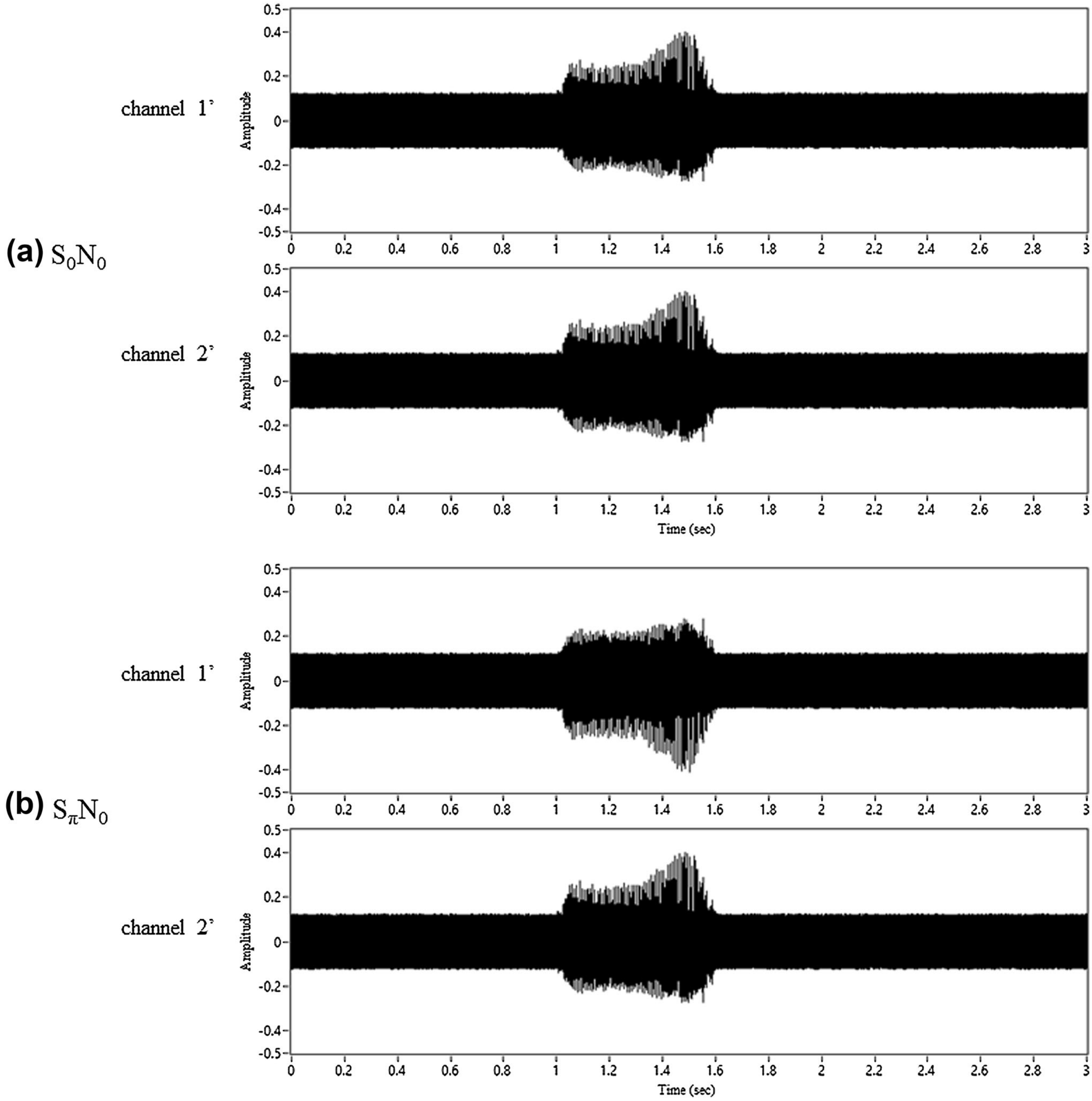

Fig. 3 Schematic diagram of interaurally in phase (S_0N_0) and interaurally in antiphase ($S_\pi N_0$) conditions. Figure shows speech signal (/u2/) combined with white noise. **a** Target signal and white noise both interaurally in phase. Upper trace is mixed signal from output of channel 1' (refer to Fig. 2), and lower trace is output from channel 2'. **b** Target signal interaurally in antiphase and white noise interaurally in phase. Upper trace is mixed signal from output of channel 1', and lower trace is output from channel 2'. The *y-axis* is the waveform amplitude of the signal, and the maximum waveform amplitude is 1

The white noise was delivered continuously with a fixed level of 50 dB HL (before amplification). The pure tone was set to have an initial level of 55 dB HL (before amplification) from the audiometer. It was delivered with a duration of 1 s at each test level. Before the task trials, the subjects were tested to make sure that they could hear the target signals after hearing aid amplification, and that each stimulus was above their thresholds. The detection task involved detecting the presence of a pure tone in continuous white noise under S_0N_0 and $S_\pi N_0$ conditions. The detection thresholds were determined using a two-down one-up adaptive staircase procedure [18]. The initial step size was 10 dB; it was reduced to 2 dB after three reversals. A single-interval "yes"/"no" response task was used.

The subjects were allowed to take a break for 10 min whenever they felt fatigued during the tests. The test conditions (S_0N_0 and $S_\pi N_0$) were presented in a random order to each subject.

3 Results

The purpose of this study was to measure the BMLDs in SNHL listeners at various frequencies after amplification of hearing aids. The inverter and two adders were designed to manipulate the phases of the signals in two channels and to combine these signals to produce the S_0N_0 and $S_\pi N_0$ test conditions. The phase difference between the input and output of the inverter was theoretically 180° when the inverter was on and 0° when the inverter was off. The acoustical measurement system had a precision of 0.01°, and the measured phase responses of the inverter indicated that the phase errors from 20 to 8000 Hz were smaller than 0.05° (Fig. 4).

Using white noise as the masker, this study determined the detection thresholds in the S_0N_0 and $S_\pi N_0$ conditions for pure tones at 125, 250, 500, 1000, and 2000 Hz. The BMLDs were derived from the threshold differences; that is, S_0N_0—$S_\pi N_0$. The differences in the detection thresholds in the S_0N_0 and $S_\pi N_0$ conditions at 125, 250, 500, 1000, and 2000 Hz were analyzed using paired-sample *t*-tests, with the significance threshold (α) set at 0.05 (two-tailed). The results of all subjects are presented in Table 1 and the results of subjects with mild hearing loss, moderate hearing loss, and moderately severe hearing loss are tabulated in Tables 2, 3, and 4, respectively.

The average detection threshold of all SNHL subjects was significantly lower ($p < 0.001$) in the $S_\pi N_0$ condition than in the S_0N_0 condition at 125, 250, 500, 1000, and 2000 Hz; the *t* values for the comparison of the detection thresholds between the $S_\pi N_0$ and S_0N_0 conditions are 5.5, 7.5, 8.6, 7.5, and 7.3, and the mean BMLDs (with 95 % confidence intervals, CIs) for SNHL subjects at these frequencies were 2.3 (CI 1.4–3.1), 4.8 (CI 3.5–6.1), 4.7 (CI 3.6–5.8), 4.2 (CI 3.1–5.4), and 3.7 (CI 2.7–4.7) dB, respectively. Note that the BMLD values indicate how much lower the target signals can be when they are presented interaurally in antiphase relative to presenting them interaurally in phase for listeners to still hear them in the same noisy environment.

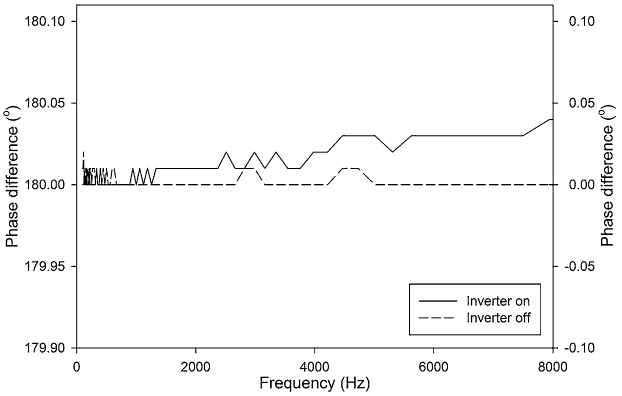

Fig. 4 Phase differences of inverter and adders from 20 to 8000 Hz when inverter was on or off. *Left* and *right y-axes* are for inverter-on and -off conditions, respectively

Table 1 Results of statistical analysis of BMLDs at 125, 250, 500, 1000, and 2000 Hz for all hearing loss subjects

	All hearing loss subjects				
Frequency (Hz)	125	250	500	1000	2000
BMLD, mean (dB)	2.3**	4.8**	4.7**	4.2**	3.7**
BMLD, CI (dB)	1.4–3.1	3.5–6.1	3.6–5.8	3.1–5.4	2.7–4.7
t	5.5	7.5	8.6	7.5	7.3
df	29	29	29	29	29

Data are mean and CI values of threshold differences (BMLD), *t* values, and degrees of freedom (df)

* $p < 0.05$; ** $p < 0.001$ in paired-sample *t* test (two-tailed)

Table 2 Results of statistical analysis of BMLDs at 125, 250, 500, 1000, and 2000 Hz for mild hearing loss subjects

	Mild hearing loss subjects				
Frequency (Hz)	125	250	500	1000	2000
BMLD, mean (dB)	2.3*	6.2**	6.2**	5.2*	3.7*
BMLD, CI (dB)	0.9–3.7	4.1–8.3	4.1–8.4	3.0–7.5	1.4–6.0
t	3.9	6.8	6.6	5.3	3.7
df	8	8	8	8	8

Data are mean and CI values of threshold differences (BMLD), *t* values, and df

* $p < 0.05$; ** $p < 0.001$ in paired-sample *t* test (two-tailed)

Table 3 Results of statistical analysis of BMLDs at 125, 250, 500, 1000, and 2000 Hz for moderate hearing loss subjects

Moderate hearing loss subjects					
Frequency (Hz)	125	250	500	1000	2000
BMLD, mean (dB)	2.1*	4.5*	3.5*	4.1*	3.5*
BMLD, CI (dB)	0.2–4.0	1.4–7.5	1.6–5.3	1.5–6.7	1.8–5.3
t	2.4	3.3	4.1	3.5	4.6
df	10	10	10	10	10

Data are mean and CI values of threshold differences (BMLD), *t* values, and df

* $p < 0.05$; ** $p < 0.001$ in paired-sample *t* test (two-tailed)

Table 4 Results of statistical analysis of BMLDs at 125, 250, 500, 1000, and 2000 Hz for moderately severe hearing loss subjects

	Moderately severe hearing loss subjects				
Frequency (Hz)	125	250	500	1000	2000
BMLD, mean (dB)	2.4*	4.0*	4.7*	3.5*	3.9*
BMLD, CI (dB)	0.9–3.9	1.9–6.1	2.5–6.9	1.9–5.1	1.7–6.1
t	3.7	4.3	4.9	5.1	4.0
df	9	9	9	9	9

Data are mean and CI values of threshold differences (BMLD), *t* values, and df

* $p < 0.05$; ** $p < 0.001$ in paired-sample *t* test (two-tailed)

For mild hearing loss subjects, the mean BMLDs are 2.3, 6.2, 6.2, 5.2, and 3.7 dB at 125, 250, 500, 1000, and 2000 Hz, respectively, those for moderate hearing loss subjects are 2.1, 4.5, 3.5, 4.1, and 3.5 dB, respectively, and those for moderately severe hearing loss subjects are 2.4, 4.0, 4.7, 3.5, and 3.9 dB, respectively. All detection thresholds were significantly ($p < 0.05$) lower in the $S_\pi N_0$ condition than in the S_0N_0 condition at these measured frequencies.

4 Discussion

The aim in this study was to measure the BMLD in SNHL listeners at various frequencies after amplification of hearing aids. The mean BMLDs at 500 and 2000 Hz for mild and moderate SNHL subjects are similar to those reported in previous studies [4, 6], with the results indicating that the mild and moderate SNHL listeners detected the target signals at lower levels when the target signals were presented interaurally in antiphase ($S_\pi N_0$) compared to when they were presented in phase (S_0N_0).

The mean BMLD values reported for moderately severe SNHL subjects by Jerger et al. were 1.2–2.0 dB [5]. Here, the mean BMLD for such subjects was 4.7 dB, which is more than twice that in the above study (at 500 Hz). In addition, for the BMLD at each measured frequency, the values for moderate and moderately severe SNHL subjects are almost on the same order. In this study, the average output level of the amplified stimulus was 86.3 dB SPL, which provided an average gain of 28.5 dB, while Jerger et al.'s study provided a stimulus of 80 dB SPL. The results of this study reveal that the amplification of the stimulus by hearing aids may help improve the BMLD of SNHL listeners. Moreover, the results of this study and those in Jerger et al.'s study reveal that the output level of the stimulus may affect the BMLD values. However, various gains were not applied for a given subject in this study. Therefore, further study may be needed to investigate the effect of gain on the corresponding BMLDs.

The statistical results of CIs at the test frequencies, the 95 % CIs of BMLDs are excluded of zero, which means the detection threshold differences (i.e., BMLDs) are larger than zero and the BMLDs are existing. The CI values obtained in the statistical analysis also indicate that the SNHL listeners could experience BMLDs at frequencies of 125, 250, 500, 1000, and 2000 Hz after amplification by hearing aids.

In addition, the statistical results indicate that SNHL listeners could experience threshold improvements of 2.3–4.8 dB from the $S_\pi N_0$ condition to the S_0N_0 condition. The results imply that the compensation for the amplification by hearing aids may partly help SNHL listeners to hear sound [19], since with amplification by hearing aids, the BMLDs of SNHL subjects were not the same as those of people with normal hearing [5]. However, the SNHL listeners could hear target signals significantly easier when the target signals were in antiphase. Therefore, the results of this study suggest that amplification by hearing aids can benefit SNHL listeners in noisy environments.

In this study, the candidate criteria included the presence of mild to moderately severe SNHL and of SNHL deviations between the two ears of no more than 15 dB from 250 to 8000 Hz. Of the SNHL listeners who participated in this study, most had a precipitous or sloping audiogram (90 %) [14]. Although this may be in accordance with the prevalence of the audiometric configuration of SNHL listeners [20], listeners present with various hearing configurations, and their corresponding BMLD performances may vary, since the presence of asymmetric hearing loss may diminish the magnitude of the BMLD [3, 5]. More experiments are required to determine the BMLD in the presence of asymmetric hearing loss or other hearing configurations when applying phase-inversion processing to bilateral hearing aids.

An increasing number of hearing aid wearers prefer to use open-canal fittings over closed-canal fittings [21]. In the past, closed-canal fittings reduced some level of ambient noise via the occluded-ear mold. Open-fitting hearing aid wearers may face a problem in noisy environments, as the noise may travel through their ear canals, making the signal unclear, so additional noise management is needed [22, 23]. A possible solution may be the application of the BMLD phenomenon in bilateral hearing aids that involves delivering the signal from a remote microphone as a frequency-modulated radio signal. The speech signal from the remote microphone may contain some noise, since the high signal-to-noise ratio of the speech signal, so the speech signal may be treated as the target signal, which could be transmitted interaurally in antiphase to the hearing aids, while the noise is simply the ambient noise surrounding the hearing-aid wearer. Hearing aid wearers may sacrifice their localization cues, but they may benefit from the BMLD phenomenon and better hear the signal in a noisy environment. This preliminary concept needs further exploration.

5 Conclusion

This study measured the BMLD in SNHL listeners at various frequencies after amplification by hearing aids. The results provide preliminary support that SNHL listeners hear target signals easier in noisy environments when the signals are presented in antiphase after amplification by hearing aids. Therefore, this study suggests that the amplification of the stimulus by hearing aids help to improve the BMLD of SNHL listeners.

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