Original Article

Advantages of Binaural Amplification to Acceptable Noise Level of Directional Hearing Aid Users

Ja-Hee Kim[1,2] · Jae Hee Lee[2] · Ho-Ki Lee[3]

[1]Department of Otorhinolaryngology-Head and Neck Surgery, Hallym University College of Medicine, Anyang; [2]Department of Audiology, Hallym University of Graduate Studies, Seoul; [3]Soree Ear Clinic, Seoul, Korea

Objectives. The goal of the present study was to examine whether Acceptable Noise Levels (ANLs) would be lower (greater acceptance of noise) in binaural listening than in monaural listening condition and also whether meaningfulness of background speech noise would affect ANLs for directional microphone hearing aid users. In addition, any relationships between the individual binaural benefits on ANLs and the individuals' demographic information were investigated.

Methods. Fourteen hearing aid users (mean age, 64 years) participated for experimental testing. For the ANL calculation, listeners' most comfortable listening levels and background noise level were measured. Using Korean ANL material, ANLs of all participants were evaluated under monaural and binaural amplification with a counterbalanced order. The ANLs were also compared across five types of competing speech noises, consisting of 1- through 8-talker background speech maskers. Seven young normal-hearing listeners (mean age, 27 years) participated for the same measurements as a pilot testing.

Results. The results demonstrated that directional hearing aid users accepted more noise (lower ANLs) with binaural amplification than with monaural amplification, regardless of the type of competing speech. When the background speech noise became more meaningful, hearing-impaired listeners accepted less amount of noise (higher ANLs), revealing that ANL is dependent on the intelligibility of the competing speech. The individuals' binaural advantages in ANLs were significantly greater for the listeners with longer experience of hearing aids, yet not related to their age or hearing thresholds.

Conclusion. Binaural directional microphone processing allowed hearing aid users to accept a greater amount of background noise, which may in turn improve listeners' hearing aid success. Informational masking substantially influenced background noise acceptance. Given a significant association between ANLs and duration of hearing aid usage, ANL measurement can be useful for clinical counseling of binaural hearing aid candidates or unsuccessful users.

Keywords. *Acceptable noise level, Binaural amplification, Directional microphone hearing aids*

INTRODUCTION

A major problem for most hearing aid users is understanding speech in background noise. Conventional speech recognition testing in quiet has been frequently used as a part of pre-fitting

hearing aid test battery, although there is little evidence of the effectiveness in predicting hearing aid outcomes [1]. A longitudinal study of hearing aid effectiveness by Bentler et al. [2] also found a weak relationship between speech recognition scores and self-assessed communication performance. Unlike the measurement of the ability to repeat the target speech presented in noise, namely speech-in-noise test, Acceptable Noise Level (ANL) testing was developed to quantify an individual's allowable signal-to-noise ratio when listening to and following a target story in babble noise [3]. The previous studies have shown that the individual ANLs were more indicative of successful hearing aid use whereas speech perception measures failed to

accurately predict the hearing aid success [3,4]. In an earlier study with a large sample size (n=191), the ANLs obtained without hearing aids were effective to predict success of 84.8% accuracy for the hearing aid users [4]. Since the individuals with lower ANLs (greater acceptance of background noise) were more likely to become successful hearing aid users than listeners with higher ANLs, an importance of ANL measure has been emphasized for clinical purpose.

Research has shown that the ANL remains relatively consistent over time, and is not influenced by listeners' age, hearing sensitivity, gender, or speech perception in noise performance [3-6]. Freyaldenhoven et al. [7] investigated the effects of monaural and binaural amplification on ANLs of the 39 binaural hearing aid users. The results showed that the ANL differences between monaural and binaural amplification did not reach statistical difference. Since the basic concept that binaural amplification provides binaural summation, binaural squelch, and binaural redundancy as well as eliminates the head shadow effects and deprivation of the unaided ear has been numerously reported [8], the finding of Freyaldenhoven et al. [7] appears somewhat contradictory.

Then, in the study of Freyaldenhoven et al. [7], what would make a non-significant difference between monaural and binaural amplification despite a well-documented strong binaural advantage? One of the possible hypotheses is the type of microphone for hearing aids. All the 39 listeners in Freyaldenhoven et al. [7] used omnidirectional mode for their hearing aids although another ANL study of Freyaldenhoven et al. [9] reported directional benefit to the noise acceptance. Numerous previous studies on the binaural advantage for hearing-impaired listeners have confirmed that the binaural and directional microphone advantages are additive [10-12]. Hornsby and Ricketts [12] directly compared sentence recognition thresholds of sixteen hearing aid users using symmetric and asymmetric directional hearing aid fittings, and found that binaural processing with directional mode maximized the speech understanding in noise. Given the additive binaural and directional benefits for speech recognition in noise, the present study compared ANL values between monaural and binaural amplification for directional microphone hearing aid users.

One of the important issues in the ANL studies would be a lack of studies that focused on the meaningfulness of background speech. In the original ANL study [3], ANLs were compared across five different noise stimuli such as babble, speech spectrum, traffic, drill, and music noise. Although similar ANL results were obtained from those different noises, the meaningfulness of speech masker has not been focused in this study. The follow-up ANL studies have mostly presented 8-talker babble noise as the only background noise. In this babble noise, information of speech masker is rarely understood, as well as the temporal fluctuations in the signal are substantially reduced than what is observed from a single-talker noise. Considering

this limitation, some recent studies in Korea have varied the number of competing talkers as background noise of ANL measure [13,14]. Those studies consistently found that the ANLs were strongly affected by the meaningfulness of competing speech in normal-hearing listeners [13] as well as cochlear implant (CI) users [14]. As the hearing-impaired users are known to be greatly affected by informational masking [15,16], the effects of informational masking from competing talkers should be also examined in the ANLs of hearing-impaired listeners. Thus, we also addressed the question of whether the ANLs of hearing aid users would be influenced by the meaningfulness of background speech noise.

In summary, the current study aimed to explore whether a greater acceptance of noise (lower ANL values) would be measured in binaural hearing than in monaural hearing for directional microphone hearing aid users. The relative binaural benefits were also determined as a function of the number of the competing talkers to examine whether the meaningfulness of speech noise would negatively affect the ANLs of hearing-impaired listeners. In addition, we determined which demographic variables would better predict the individual ANLs.

MATERIALS AND METHODS

Participants

Seven young normal-hearing listeners participated for a pilot testing, and fourteen binaural hearing aid users participated for an experimental testing. All the seven young normal-hearing listeners (mean age, 27 years; range, 24 to 29 years; 2 males, 5 females) had thresholds of 15 dB HL or better in the frequencies from 250 Hz to 8,000 Hz at the octave scale. Fourteen listeners with sensorineural hearing loss (7 males and 7 females) between 32 and 84 years (mean age, 64 years) had unaided pure-tone
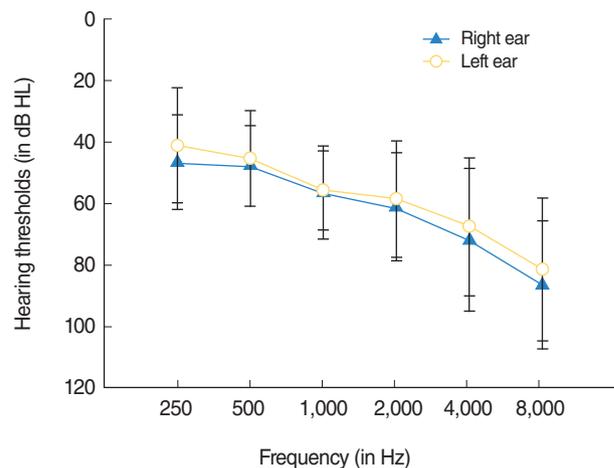

Fig. 1. Comparison of mean hearing thresholds (error bars, standard deviation) from 250 to 8,000 Hz at the octave scale between right and left ears.

Table 1. Demographic information of 14 hearing-impaired listeners

| Subject | Age (year) | Gender | Duration of hearing aid usage (month) | | Ear for monaural ANL testing | Information of hearing aids | | | | | |
| | | | | | | R | | | L | | |
			R	L		Type	No. of channel	Fitting formula	Type	No. of channel	Fitting formula
S1	67	M	72	1	R	ITE	9	NAL-NL1	ITE	9	NAL-NL1
S2	32	F	3	48	L	RIE	17	Audiogram +	RIE	17	Audiogram +
S3	60	F	9	9	R	RIE	17	Audiogram +	RIE	17	Audiogram +
S4	43	M	1	1	R	RIE	3	Audiogram +	RIE	17	Audiogram +
S5	82	M	3	3	L	BTE	17	NAL-NL1	BTE	17	NAL-NL1
S6	84	M	60	36	R	RIE	17	NAL-NL1	RIE	17	NAL-NL1
S7	77	F	3	3	R	RIE	17	NAL-NL1	RIE	17	NAL-NL1
S8	59	F	4	36	L	RIE	17	Audiogram +	RIE	17	Audiogram +
S9	78	F	1	1	R	RIE	17	Audiogram +	RIE	17	Audiogram +
S10	59	M	12	12	R	RIE	17	NAL-NL1	RIE	17	NAL-NL1
S11	65	F	1	1	R	RIE	17	NAL-NL1	RIE	17	NAL-NL1
S12	70	F	1	1	R	RIE	17	Audiogram +	RIE	17	Audiogram +
S13	58	M	2	2	R	RIE	17	Audiogram +	RIE	17	Audiogram +
S14	48	M	12	12	R	RIE	17	Audiogram +	RIE	17	Audiogram +
Mean	64.1		13.11	11.86							

R, right ear; L, left; ANL, Acceptable Noise Level; ITE, in-the-ear hearing aid; RIE, receiver-in-the-ear hearing aid; BTE, behind-the-ear hearing aid; NAL-NL1, National Acoustic Laboratories' nonlinear fitting procedure, version1.

threshold average (PTA) across 500, 1,000, 2,000 Hz of 54.1 dB HL. All the hearing-impaired listeners were recruited from Soree Ear Clinic, from March to December 2010, and were agreed with research participation prior to the experimental testing.

Fig. 1 displays symmetric hearing loss of 14 hearing-impaired listeners by plotting each ear's unaided hearing thresholds. The criteria for binaural hearing aid users include duration of hearing aid usage more than one month. All the participants used multichannel digital hearing aids. Table 1 details the listeners' age, gender, and other information of the hearing aids with directional microphone. To select the test ear for monaural amplification, the ear which has used hearing aid longer was selected. If both ears have the same duration of hearing aid experience, the right ear was chosen for the monaural testing. The hearing aids were fitted to best meet their preference and needs, and were not adjusted for the purpose of this study.

Stimuli

For the ANL measurement, two target stories (one male and one female) and five types of competing speech maskers (1-male, 1-female, 2-, 4-, and 8-talker speech masker) recorded in the previous study [13] were used. Here, the 2-, 4-, and 8-talker speech maskers were derived from the same number of male or female talkers. When the target and competing speech materials were recorded in the previous study [13], the average root-mean-squared (RMS) values of all speech materials were controlled via Adobe Audition ver. 3.0 (Adobe Systems Incorporated, San Jose, CA, USA) to equalize the overall intensity.

Procedure and equipment

The ANL testing was administered according to the procedure described in the earliest study [3] as follows. Before the experimental testing, all the listeners were given oral and written instructions on how to signal the examiner to increase or decrease the intensity of the signal. The starting level for determining the most comfortable listening level (MCL) was 30 dB HL, and the intensity of target story was adjusted in 5 dB steps and 2 dB steps for exploring listeners' listening range first and then finally selecting the loudness level that is most comfortable to each participant, respectively. When the listeners' MCL was established, the target story continued to be presented at MCL and then the background noise was turned on. Finally, the listener was asked to report the maximum or highest level at which the background noise was still accepted or tolerable, called the background noise listening level (BNL). The ANL is the difference between the MCL and the BNL, being expressed in dB. Given this procedure, the lower ANL represents a higher acceptance of background noise.

The ANL evaluation was performed in both monaural and binaural amplification. To avoid any learning or fatigue effect, the order of testing was randomized for the listening condition and the 5 competing speech maskers, yet each of them presented once. The ANL material was presented by MP3 player (iAudio 9, Cowon, Seoul, Korea) and routed through an audiometer (Orbiter 922, GN Otometrics, Copenhagen, Denmark). Both speech and noise stimuli were presented through sound-field loudspeaker (R-300, InterM, Yangju, Korea) located at 0 degrees azimuth nearly 1 m from the participant. The output levels of

the target and background speech were calibrated using sound level meter (Type 2150L, Brüel and Kjær, Skodsborgvej, Denmark) in order to present each signal at 65 dB sound pressure level. The output level was periodically checked by the experimenter during testing.

Analysis

Statistical analyses were conducted using SPSS ver. 18.0 (SPSS Inc., Chicago, IL, USA). Two independent variables were listening condition (monaural, binaural) and the number of competing talkers (1-male, 1-female, 2-, 4-, and 8-talker). Dependant variable was ANL value of each participant. With the variables above, a two-way analysis of variance (ANOVA) with repeated measures was executed. Bonferroni post-hoc analyses were also performed as multiple comparison testing. To further examine the relationship between the ANLs and participants' demographic information such as age, hearing threshold, duration of hearing aid usage, Pearson correlation analyses were conducted.

Pilot testing

In the pilot testing, seven young normal-hearing adults were tested in order to compare the present and previous data [13]. Results showed that the average ANL of young adults in the present study (n=7) was 7.7 dB when collapsed across five speech maskers (range, 5 to 10 dB). The mean ANL of 20 young adults in the previous study [13] was 9.9 dB across five speech maskers (range, 8 to 12 dB). Results of independent *t*-test revealed no significant difference (*P*>0.05) in listeners' ages and ANLs between two studies, verifying the correct procedure and instruction for the ANL testing.
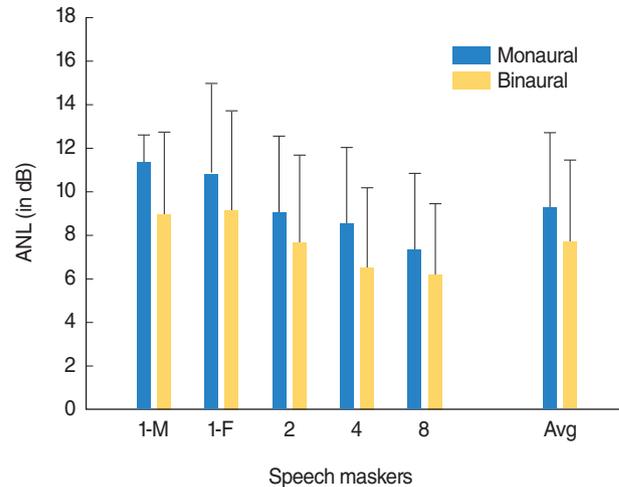

Fig. 2. Comparison of the mean Acceptable Noise Levels (ANLs) (error bars, standard deviation) of 14 hearing-impaired listeners obtained with monaural and binaural amplification for five different speech maskers. 1-M, one-male; 1-F, one-female; 2, 2-talker; 4, 4-talker; 8, 8-talker maskers; Avg, averaged across five speech maskers.

RESULTS

Group data

The present study investigated the effects of listening condition and the number of competing talkers on the ANL of 14 hearing aid users. Overall results are plotted in Fig. 2. In general, the average ANLs were 9.23 and 7.67 dB for monaural and binaural amplification, collapsed across five different speech maskers, as shown at the far right of Fig. 2. The mean ANLs for 1-male, 1-female, 2-, 4-, 8-talker maskers were 10.8, 10.6, 9.0, 8.5, and 7.3 dB in monaural listening condition, and were 8.9, 9.1, 7.6, 6.5, and 6.1 dB with binaural amplification. A two-way ANOVA with repeated measures was carried out to investigate the effects of two variables on ANLs. Results indicated a greater amount of noise acceptance (lower ANL) with binaural amplification than with monaural amplification (*P*<0.01). Noise acceptance became significantly poorer with smaller number of competing talkers than with multitalker noise such as babble (*P*<0.01). Bonferroni-adjusted multiple paired-comparisons were conducted to determine which comparisons made a significant effect of the number of competing talkers. Results showed that there were no significant ANL differences between 1-male and 1-female speech maskers, and also between 4- and 8-talker maskers. All the rest of other comparisons revealed significant ANL differences (ANLs with 1-male or 1-female > ANLs with 2-talker > ANLs with 4-talker or 8-talker noise). The interaction between two variables was not significant (*P*>0.05), meaning that the binaural advantages to tolerate noise appeared to be significant, regardless of the noise type.

Individual data

When collapsed across five noise types, 11 listeners out of 14 listeners accepted more noise with binaural amplification than with monaural amplification. Here, the present study confirmed how many subjects had low- and high-ANL based on the criteria of Nabelek et al. [4]. According to their findings, the ANL values are categorized into three levels such as low-, mid-, and high-ANLs. Individuals who have low ANLs (6 dB or lower) can tolerate background noise more, thus being generally successful hearing aid users. In contrast, individuals who have high ANLs (14 dB or greater) poorly accept the background noise, thus being generally unsuccessful hearing aid users. People with mid ANLs (7–13 dB) may or may not be successful with hearing aids. In Fig. 3, the individual and mean ANLs are separately plotted for each of the five speech maskers. Here, the dashed lines show 6-dB and 14-dB ANLs to visualize better who had low and high ANLs, respectively. When the number of competing talker was increased from 1 to 8, the number of participants showing high ANLs decreased, yet the number of participants showing low ANLs increased. Especially with 8-talker babble,
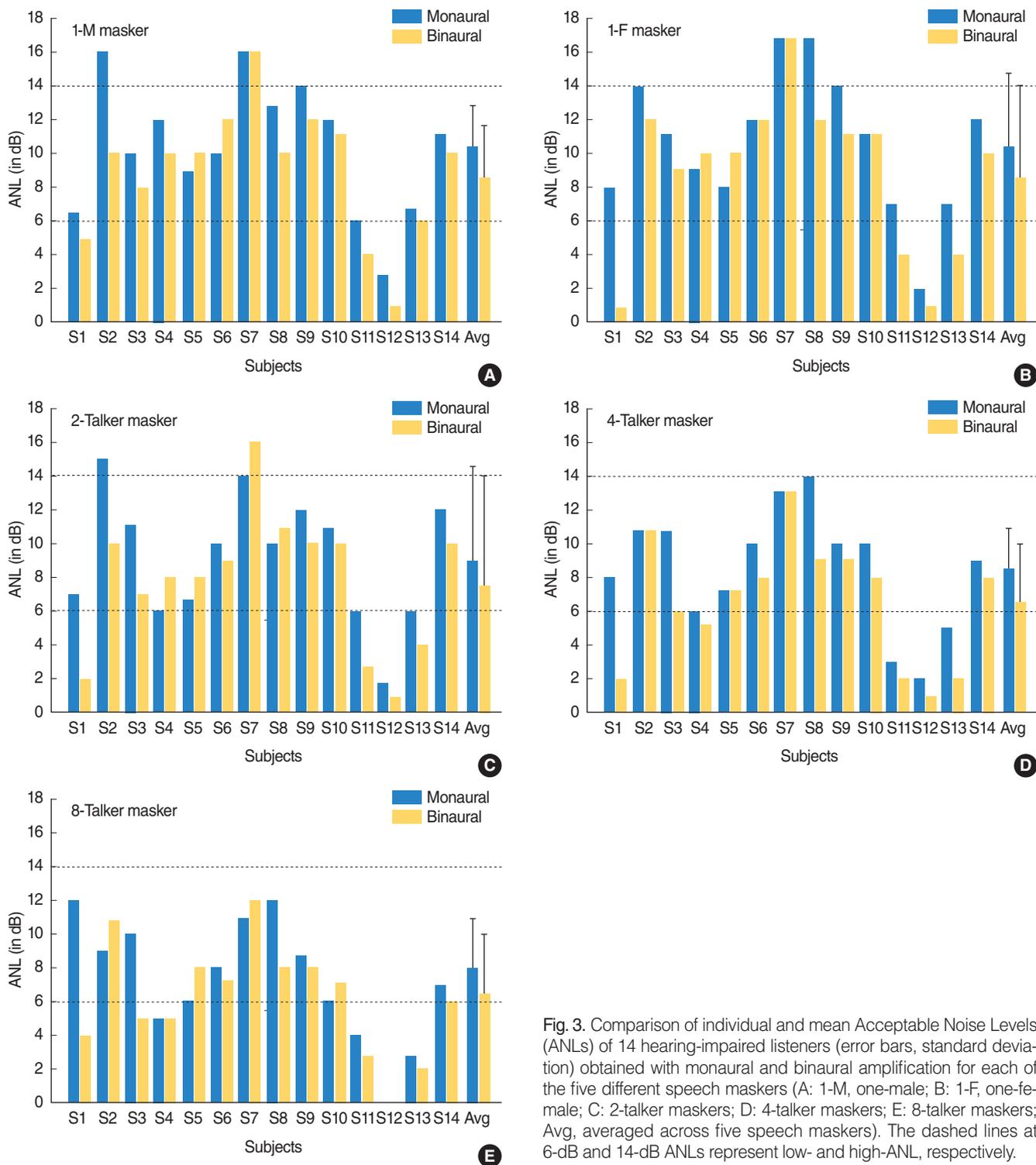
Fig. 3. Comparison of individual and mean Acceptable Noise Levels (ANLs) of 14 hearing-impaired listeners (error bars, standard deviation) obtained with monaural and binaural amplification for each of the five different speech maskers (A: 1-M, one-male; B: 1-F, one-female; C: 2-talker maskers; D: 4-talker maskers; E: 8-talker maskers; Avg, averaged across five speech maskers). The dashed lines at 6-dB and 14-dB ANLs represent low- and high-ANL, respectively.

no subject showed high ANLs, yet 9 out of 14 subjects had low ANLs for either monaural or binaural condition or for both, meaning that more participants became tolerant to background babble noise. Another finding was that some subjects had relatively greater binaural benefits while some showed relatively smaller change in ANLs between binaural and monaural amplifications. For example, some subjects (S1, S3, S9, S11, S13, and S14) consistently showed the binaural benefit in ANLs across all the conditions, whereas binaural benefits of some subjects (S2, S4, S6, S8, S10, and S12) appeared inconsistent across the conditions. Interestingly, two subjects (S5, S7) showed binaural disadvantages in accepting noise across most of noise conditions.

Given the individual variability in the amount of binaural ANL benefits, we calculated each individual's binaural benefit by subtracting binaural ANL from monaural ANL (monaural ANL–binaural ANL). Pearson correlation analysis was then conducted to examine the relationship between individual binaural benefits and demographic information such as listeners' age, hearing aid usage, and aided hearing thresholds. Results showed that the individual binaural benefits were significantly related to hearing aid usage (correlation coefficient r, 0.56; $P<0.05$), but not related to age or aided hearing thresholds ($P>0.05$) similar to the previous findings [3-5]. This indicates that the longer the use of hearing aids, the larger the amount of binaural benefit, regardless of listeners' age or hearing sensitivity.

DISCUSSION

Although ANL appears to be a quick, clinician-friendly procedure to measure directional microphone benefit [9], the ANLs with monaural versus binaural amplification were evaluated for only omnidirectional microphone users [7]. The previous study [7] in which all 39 listeners used omnidirectional microphone found no significant difference in ANL values between monaural and binaural amplification.

In contrast to this, the present study demonstrated that a greater amount of noise could be accepted with binaural amplification than with monaural amplification for directional microphone hearing aid users. Not only in the group data, when averaging the data of 5 speech maskers, 11 listeners out of 14 were willing to accept a higher level of background noise with binaural amplification than with monaural amplification. As one of the possible explanations on the contradictory findings between the current data of directional microphone users and the previous data of omnidirectional microphone users would occur from the different frequency responses measured with omnidirectional and directional modes [11]. Additionally, any additive binaural and directional benefits [10-12] would affect binaural use of directional microphone to accept the noise. In an earlier study the bilateral directional fitting was advantageous even when the moderately reverberant situation was reflected [12]. Also, listeners' acclimatization to directional hearing aids would influence individuals' noise acceptance given that the present data revealed a significant relationship between listeners' hearing aid usage and ANLs.

The binaural amplification advantages have been confirmed primarily using subjective and objective recognition measures. An earlier research using subjective measure found that 27 of 30 participants preferred to use binaural hearing aids because of improved speech clarity, better speech understanding in noise, and ease of listening [17]. In another study, the use of two hearing aids appeared to be advantageous to reduce listening efforts and to improve social competence and emotional well-being [18] when the degree of subjective binaural benefits was examined through Speech, Spatial, and Qualities of Hearing scale (SSQ) [19]. The binaural benefit was also obtained from various objective measures such as speech recognition and localization [20,21]. Beyond the conventional objective and subjective measures such as recognition or localization performance in the previous studies, the present study directly measured the maximum amount of noise that each individual was willing to tolerate. Taken the present and earlier findings together, one could conclude that the use of binaural directional-microphone amplification facilitates the abilities to tolerate noise as well as to understand speech in noise, at least when the signals are coming from the front. In most ANL studies including the present study, the signals were delivered through one loudspeaker located at 0 degrees azimuth, meaning that the sounds were not presented from the side or the rear. Considering that sounds from the side and the rear are attenuated whereas the sounds from the front are preferred in a directional microphone [11,22], it is essential that further research be conducted on binaural advantages using various spatial sources.

Another purpose of this study was to determine whether the ANLs would be strongly affected by meaningfulness of background speech for hearing-impaired listeners. As described earlier, most of the previous ANL research has used babble noise as the only background noise, considering the similar ANLs across five unintelligible noises in the original ANL study [3]. There are only a few ANL studies which have focused on the meaningfulness of speech masker. Gordon-Hickey and Moore [23] used three types of speech maskers (intelligible, reversed, and unfamiliar speech) and evaluated the ANLs of normal-hearing listeners. Results showed that the young hearers accepted more amount of reversed or unfamiliar speech noise than when the noise was intelligible, emphasizing a need of more research on the effects of noise type on ANLs. As follow-up research, two ANL studies in Korea [13,14] concerned the meaningfulness of speech masker to ANLs, and found that the ANLs were significantly affected by meaningfulness of competing speech for both normal-hearing listeners [13] and CI users [14]. The results of the present study also determined that the highest ANL was obtained from 1-talker masker, suggesting that the least amount of noise was accepted when the masker speech was highly intelligible, thus, the most distracting or confusing. In contrast, the lowest ANL was obtained from 8-talker masker because 8-talker babble noise would be the least intelligible and less annoying, allowing more noise to be accepted. This supports the previous data that hearing impaired listeners are more susceptible to informational masking, possibly reflecting their peripheral and central processes [15,16]. Since the ANLs of CI users appear to be influenced by target-masker similarity [14] which is one of the robust factors affecting informational masking [24,25], more studies are needed to investigate how much the uncertainty or target-masker similarity would affect the ANLs. In addition,

considering that informational masking can be overcome by improving listeners' auditory attention toward the target story [26], more studies are required to focus on the efficacy of systematic auditory training to overcome negative impact of informational masking. If it turns out that auditory training substantially improves background noise acceptance like speech understanding in noise, then the auditory training should be considered especially for high-ANL listeners.

One of the limitations in this study is no comparison of subjective benefits between binaural and monaural amplification as well as no estimate of any relationships between ANLs and self-reports. Only limited research explored possible associations between ANLs and subjective reports of hearing-impaired listeners. For example, when the ANLs of twenty postlingually-deafened CI users were evaluated [27], the results revealed that the less ability of CI users to accept noise (higher ANLs) was significantly associated with greater difficulties perceived in real-life communication. This was true for another study of CI users [14] which revealed that CI users who could accept more noise actually reported more improvement on sound quality with CI use. Besides the subjective reports, we should be cautious of subjective preference to binaural versus monaural amplification. Some researchers [28] reported that binaural hearing was preferred when listening in quiet for most subjects, yet some listeners preferred monaural listening in noise. Other studies also revealed that some listeners would be more susceptible to binaural interference and thus, their speech recognition or localization in noise would be poorer with binaural hearing aids than with monaural device [29,30]. To answer the questions of whether binaural ANL advantages are related to subjective communication abilities with binaural hearing aids or subjective preference to binaural amplification, future research is needed to investigate relationship among those variables for better clinical counseling or advice.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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