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Benefits of incorporating the adaptive dynamic range optimization amplification scheme into an assistive listening device for people with mild or moderate hearing loss

Hung-Yue Chang, MS[a], Ching-Hsing Luo, PhD[a], Tun-Shin Lo, MS[b,c], Hsiao-Chuan Chen, PhD[d], Kuo-You Huang, PhD[b], Wen-Huei Liao, MD, PhD[e,f], Mao-Chang Su, MD, PhD[b,c,g], Shu-Yu Liu, MS[b], and Nan-Mai Wang, MS[b]

[a]Department of Electrical Engineering, National Cheng-Kung University, Tainan, Taiwan; [b]School of Speech Language Pathology and Audiology, Chung Shan Medical University, Taichung, Taiwan; [c]Dept. of Otolaryngology, Chung Shan Medical University Hospital, Taichung, Taiwan; [d]Graduate Institute of Audiology and Speech Therapy, National Kaohsiung Normal University, Kaohsiung, Taiwan; [e]School of Medicine, National Yang Ming University, Taipei, Taiwan; [f]Department of Otolaryngology, Taipei Veterans General Hospital, Taipei, Taiwan; [g]School of Medicine, Chung Shan Medical University, Taichung, Taiwan

ABSTRACT

This study investigated whether a self-designed assistive listening device (ALD) that incorporates an adaptive dynamic range optimization (ADRO) amplification strategy can surpass a commercially available monaurally worn linear ALD, SM100. Both subjective and objective measurements were implemented. Mandarin Hearing-In-Noise Test (MHINT) scores were the objective measurement, whereas participant satisfaction was the subjective measurement. The comparison was performed in a mixed design (i.e., subjects' hearing status being mild or moderate, quiet versus noisy, and linear versus ADRO scheme). The participants were two groups of hearing-impaired subjects, nine mild and eight moderate, respectively. The results of the ADRO system revealed a significant difference in the MHINT sentence reception threshold (SRT) in noisy environments between monaurally aided and unaided conditions, whereas the linear system did not. The benchmark results showed that the ADRO scheme is effectively beneficial to people who experience mild or moderate hearing loss in noisy environments. The satisfaction rating regarding overall speech quality indicated that the participants were satisfied with the speech quality of both ADRO and linear schemes in quiet environments, and they were more satisfied with ADRO than they with the linear scheme in noisy environments.

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KEYWORDS
adaptive dynamic range optimization (ADRO); assistive listening device (ALD); Mandarin Hearing-In-Noise Test (MHINT)

Introduction

Assistive listening devices (ALDs) have been widely used by people with hearing loss. In contrast to hearing aids, ALDs are not regulated by the U.S. Food and Drug Administration and, therefore, are dispensed within the consumer market via drug stores, supermarkets, and mail order, without the necessity of fitting by an audiologist. ALDs can be used alone or coupled with hearing aids through near-field magnetic induction technology. By applying the wireless technologies of FM radio signals, induction loop systems, infrared light, or Bluetooth devices, ALDs can be used to transmit sounds from sources at a far distance (e.g., involving a television or a classroom lecture) to body-worn or ear-level devices; thus, the signal-to-noise ratio (SNR) is significantly improved (Hawkins & Schum, 1985). Without the transmitter, the body-worn device is also an option to hearing aids for amplifying environmental sounds by using the local microphone (Hartley, Rochtchina, Newall, Golding, & Mitchell, 2010). Other types of ALD can transmit sounds from phones or multimedia players that are either wired or wireless.

As the distance between the sound source and the listener increases, the SNR decreases (Boothroyd & Iglehart, 1998). Placing a remote microphone close to a person speaking, or a wireless transmitter to a television, can bring the most benefit to senior people who experience hearing loss (Jerger, Chmiel, Florin, Pirozzolo, & Wilson, 1996; Jerger, Chmiel, Wilson, & Luchi, 1995); however, it is often difficult to educate elderly people regarding the correct placement of a microphone for achieving a more favorable SNR (Lesner, 2003). Many people use ALDs with two technologies in particular: televisions and telephones. Some factors are significantly associated with the use of ALDs, such as the education level, experience of hearing aid use, and degree of hearing loss (>40 dB HL; Hartley et al., 2010). Recent studies reported that approximately 5% of hearing-aid users did not use or rarely used their hearing aids (Bertoli et al., 2009; Uriarte, Denzin, Dunstan, Sellars, & Hickson, 2005; Vuorialho, Sorri, Nuojua, & Muhli, 2006); however, simple solutions such as ALDs can be options in the aforementioned scenarios.

Without a remote microphone, ALDs with a microphone fitted to the body-worn receiver were less beneficial than hearing aids (Boothroyd & Iglehart, 1998). Traditional ALDs provide a linear amplification scheme to increase the SNR; however, the limitations of the linear circuits entail an uncomfortable sensation when high-level input signals are received, especially in noisy environments (Farrow, Tatum, Michel, & McCabe, 2012). In a previous study, when linear ALDs were used for watching television, the loud background sound tracks appeared to be annoying and distracting; thus, the speech intelligibility was reduced (Aberdeen & Fereiro, 2014). Considering that the

CONTACT Tun-Shin Lo rexshing@csmu.edu.tw School of Speech Language Pathology and Audiology, No.110, Sec.1, Jianguo N. 4 Rd., Taichung, 40201, Taiwan.

hearing dynamic range decreases with increasing hearing loss (Fowler, 1965; Moore & Glasberg, 1993), appropriate compressor and noise-reduction strategies commonly used in hearing-aid technology are a necessary consideration in ALD design. Some recently distributed ALDs include wide dynamic range compression (e.g., Etymotic The BEAN [Etymotic, 2015]) or output compression (e.g., Sound World Solution CS50 [Bailey, 2014]); however, their clinical benefits compared with those of a linear system remain unknown.

The adaptive dynamic range optimization (ADRO) processing strategy, which adaptively optimizes speech signals in each narrow frequency band to fit a person's hearing dynamic range, provides improved amplification for soft sounds and comfort for loud sounds with compression schemes, and does so without reducing sound quality or speech intelligibility in noisy environments. ADRO involves using four fuzzy logic rules to control the gain at each narrow frequency band; namely, comfort, audibility, hearing protection, and background noise rules (Blamey, 2005). Several clinical trials using hearing aids and cochlear implants demonstrated the benefits of ADRO processing (Blamey, Fiket, & Steele, 2006; Iwaki, Blamey, & Kubo, 2008; Mispagel & Valente, 2006; Wolfe, Schafer, John, & Hudson, 2011; Zakis, Hau, & Blamey, 2009). Based on these positive results, ADRO may offer a high-quality amplification scheme for ALDs.

The aim of this study was to demonstrate the benefits of incorporating an ADRO scheme into a body-worn ALD over those of a commercial linear-scheme ALD, Sound ID SM100, in quiet and noisy environments. The benefits between mild and moderate hearing-loss groups were compared to reveal which group benefits more from ALD use. The Mandarin Hearing-In-Noise Test (MHINT) was used to assess the benefits for objective results, whereas the participants' satisfaction rating regarding overall speech quality was collected for subjective results. This study hypothesized that listeners who had mild or moderate hearing loss received better benefits, subjectively and objectively, with the ADRO-ALD than with the linear-ALD, in both quiet and noisy environments.

Materials and methods

ALDs

The ALD developed for this study was a binaural in-the-ear earphone, in which a microphone was fitted to receive environmental sounds and a nonoccluded ear plug was fitted to reduce the occlusion effect on each side of the earpiece. Each earpiece was connected to a control box by wires. A digital volume control located at the control box consisted of 15 steps with an increment of 1.8 dB per step. The digital signal processor (DSP) algorithms, which were coded in the Kalimba DSP of a CSR BlueCore5™ Multimedia Bluetooth chip, contained three parts: an ADRO scheme to enhance speech intelligibility; a feedback cancellation algorithm, including steady and adaptive feedback controls; and a noise suppression algorithm to suppress static environmental noises, such as fan noise. The audio path of these DSP algorithms is illustrated in Figure 1. The ALD was designed to fit a Bluetooth integrated circuit (IC) for enabling future studies to establish a wireless connection to a remote microphone.

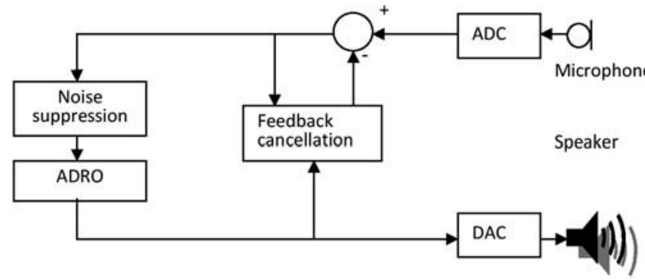

Figure 1. Audio signal path.

Two types of amplification modes were designed: a medium profile for gentle-slope hearing loss referenced from the average audiogram of 60 to 69 years old in the Blue Mountains study (Chia et al., 2007), and a maximum profile for high-tone or sloping-type hearing loss referenced from the audiogram of the early stages of noise-induced hearing loss (Dobie, 2007). The coupler gains at various frequencies of the medium and maximum profiles are listed in Table 1.

The Sound ID SM100, with a nearly linear amplification scheme, as shown in the input–output curves in Figure 2, was compared with the ADRO-ALD in this study. The Sound ID SM100 is a monaural Bluetooth headset that employs a noise-reduction function and three hearing-enhancement programs: mild, moderate, and strong (SoundID, 2007). The coupler gains at various frequencies of the three programs are listed in Table 2. The digital volume control of the SM100 consisted of nine steps for adjusting the volume in increments of 1.5 dB per step.

The maximum coupler gains of the ADRO-ALD at a 60-dB sound pressure level (SPL) input were 21 dB and 25 dB for medium and maximum profiles, respectively, whereas those of

Table 1. Coupler gains at 90-dB and 60-dB SPL inputs of medium and maximum profiles of the ADRO-ALD.

Profile	Input	250	500	1,000	2,000	3,000	4,000	Hz
Medium	90 dB SPL	4	3	4	9	14	10	dB
	60 dB SPL	4	3	4	11	21	15	dB
Maximum	90 dB SPL	4	3	4	9	14	10	dB
	60 dB SPL	4	3	4	12	25	19	dB

Note. Data were measured under full-on condition with a 2-cc coupler.

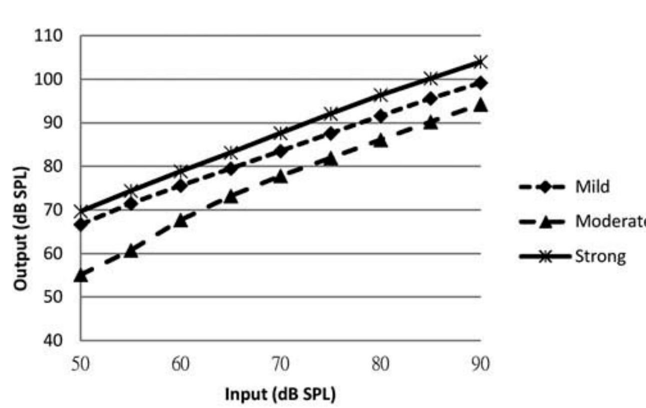

Figure 2. Input–output curves of SM100. Data were measured with a 2-cc coupler at 2,000 Hz.

Table 2. Coupler gains at 90-dB and 60-dB SPL inputs of three programs of SM100.

Profile	Input	250	500	1,000	2,000	3,000	4,000	(Hz)
Mild	90 dB SPL	10	9	8	8	13	−3	dB
	60 dB SPL	11	11	11	16	22	6	dB
Moderate*	90 dB SPL	−6	−3	−1	2	11	−4	dB
	60 dB SPL	−7	−3	−1	4	21	6	dB
Strong	90 dB SPL	13	13	13	15	21	6	dB
	60 dB SPL	13	13	14	20	28	14	dB

Note. Data were measured under full-on condition with a 2-cc coupler.
*Moderate profile appeared to be the mild profile with a low cut filter. Five SM100 samples were measured and had similar results.

the SM100 were 22 dB, 21 dB, and 28 dB for mild, moderate, and strong profiles, respectively. Therefore, the maximum coupler gains were similar between the two devices, and could therefore be used in the following tests.

Measurements

MHINT, a standard Mandarin sentence test used in large-scale clinical studies over the past decade, was adopted in this study for the objective measurement. The HINT Pro Audiometric System (Version 7.2.0.i01 Rev A) was utilized to assess the subjects' speech performance. It comprised 12 lists, with 20 sentences in each list, and 10 words in each sentence (Wong, Soli, Liu, Han, & Huang, 2007).

The subjects were seated in a soundproof room, facing a speaker from which the speech signals were produced, as illustrated in Figure 3. The speaker was 1 m from the subject and was calibrated using a standard procedure before the test. Under the quiet condition, no noise was played. Under the noise condition, the same speaker produced A-weighted speech-shaped noises at a fixed level of 65 dBA throughout the test. The presentation level of the sentences was adjusted adaptively by the HINT Pro system to determine the sentence reception threshold (SRT) under quiet and noise conditions, with the subject recognizing 50% of the sentences. The initial SNR was started from 0 dB under the noise condition in this study.

Questionnaire

A questionnaire was designed to assess the overall speech quality in quiet and noisy environments based on indoor and outdoor trials following the audiometric tests. Other standard questionnaires, such as the Abbreviated Profile of Hearing Aid Benefit (APHAB) and the International Outcome Inventory for Hearing Aids (IOI-HA), were not selected because they are used to assess participant satisfaction in various scenarios, whereas our questionnaire mainly focused on the overall sound quality in quiet and noisy environments. The rating system was based on a 5-point scale (Alcántara, Moore, Kühnel, & Launer, 2003): *very satisfied, satisfied, neutral, dissatisfied*, and *very dissatisfied*. The questionnaire is presented in the appendix.

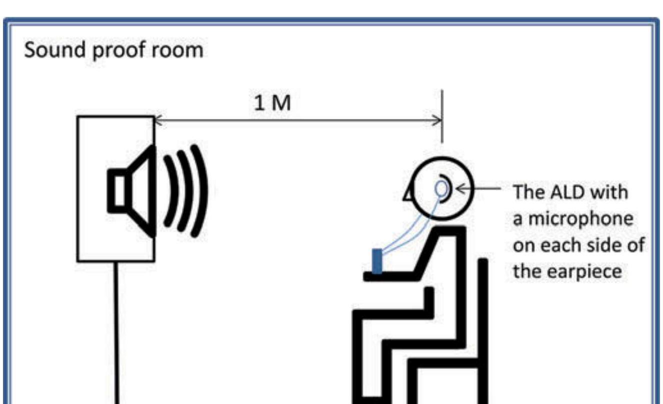

Figure 3. Measurement setup.

Participants

A total of 17 native Mandarin speakers (12 men and five women) participated in this study. The ages ranged from 21 to 68 years with a mean age of 42 years. Nine participants (six men and three women) were recruited in the mild-loss group, and eight participants (six men and two women) were in the moderate-loss group. The range of the average hearing thresholds (at 500 Hz, 1,000 Hz, and 2,000 Hz) in the mild-loss group was 26 dB HL to 40 dB HL, whereas it was 41 dB HL to 55 dB HL in the moderate-loss group. Central neural hearing disorder was excluded by physicians. According to the case history, the subjects experienced no conversational difficulties before first noticing their hearing loss. Among the 17 participants, only one in the mild-loss group had experience using a hearing aid. Table 3 shows the gender, average ages, hearing thresholds, and word discrimination scores (WDSs) for each group.

Due to small sample size in each group, the power analyses were conducted to test the sufficiency of sample size. In general applications, the power (1-β) higher than 0.8 is considered sufficient of rejecting null hypothesis (Pagano & Gauvreau, 2000). The protocol was approved by the Chung Shan Medical University Hospital Institutional Review Board; all participants provided informed consent.

Procedures

All audiometric tests were conducted in a soundproof room. The following data were collected sequentially for each participant before they tried the ALD: pure tone thresholds (air

Table 3. Mean and standard deviation for ages, pure tone averages (PTA), speech reception thresholds (SRT), and WDSs.

Hearing impairment	Ave. age yr	Male	Female
Mild (*n* = 9)	44(17)	6	3
Moderate (*n* = 8)	39(16)	6	2
Total (*n* = 17)	42(16)	12	5

Hearing impairment	PTA[t] dB HL	PTA[b] dB HL	SRT[t] dB HL	SRT[b] dB HL	WDS[t] %	WDS[b] %
Mild (*n* = 9)	31(9)	31(8)	31(8)	31(8)	97(4)	97(2)
Moderate (*n* = 8)	44(8)	47(5)	43(8)	45(5)	82(6)	81(6)
Total (*n* = 17)	37(11)	38(10)	36(10)	37(10)	90(9)	89(9)

Note. PTA is the average threshold at frequencies of 500, 1,000, and 2,000 Hz.
[t]Test ear data.
[b]Binaural average data.

and bone conductions), speech reception thresholds, WDSs, uncomfortable levels (UCLs), and tympanograms.

Each participant tried the ADRO-ALD with medium and maximum profiles first (linear Sound ID SM100 with mild, moderate, and strong profiles), and then chose the preferred profile while engaging in a normal conversation with one of the researchers in the test room. The volume was set at the most comfortable level by each participant. The settings were confirmed and recorded by the researcher. The participants then wore and used the ADRO-ALD, or linear Sound ID SM100, indoors and outdoors for more than 30 minutes.

For the objective measurement, the data of the following conditions were collected randomly for the two groups of subjects: quiet versus noisy, as well as linear Sound ID SM100 versus ADRO-ALD. The ADRO-ALD was worn and tested both monaurally and binaurally. For the monaural condition, the preferred aided ear was used as the test ear.

For the subjective measurement, the subjects were asked to rate the overall speech quality of the two devices in quiet and in noisy environments, regardless of whether the devices were worn monaurally or binaurally.

Results

Table 4 shows the participants' preferred profiles for both the ADRO-ALD and SM100. Among the nine participants in the mild-loss group, two chose the maximum profile for the ADRO-ALD; five subjects preferred the strong profile for the SM100. All eight participants in the moderate-loss group selected the maximum profile for the ADRO-ALD and the strong profile for the SM100. The following MHINT scores and satisfaction ratings were obtained with these profiles selected by the participants.

Speech in quiet environments

MHINT SRTs in quiet environments under unaided, binaurally ADRO-aided, monaurally ADRO-aided, and monaurally SM100-aided conditions are shown in Figure 4. For the mild and moderate hearing-loss groups, a one-way ANOVA test indicated no significant difference among the mean SRT values obtained in the quiet environment under the four test conditions. However, for all test conditions, the mean SRTs in the quiet environment differ significantly between the mild and the moderate groups ($F_{(1,68)} = 75.684$, $p < 0.001$; 1-$\beta = 1.0$). As expected, the data show that the SRTs of the mild-loss group were significantly lower than those of the moderate-loss group in the quiet environment.

Speech in background noise

The MHINT SRTs in the noisy environment under the unaided, binaurally ADRO-aided, monaurally ADRO-aided, and monaurally SM100-aided conditions are shown in Figure 5. Each dB change in SNR represents an approximately 9% change in speech intelligibility (Wong et al., 2007). For the mild and moderate hearing-loss groups, the one-way ANOVA test showed a significant difference among the mean results acquired from the four test conditions ($F_{(3,68)} = 4.269$, $p < 0.01$; 1-$\beta = 0.840$). Additional results of multiple comparisons (post-hoc test using the Tukey method) revealed a significant difference between the results obtained under unaided and monaurally ADRO-aided conditions ($p < 0.05$), and between unaided and binaurally ADRO-aided conditions ($p < 0.01$); however, no significant difference was observed between the results obtained under unaided and monaurally SM100-aided conditions, or between those obtained under monaurally and binaurally ADRO-aided conditions. For all test conditions, the SRTs of the mild-loss group were significantly lower than those of the moderate-loss group ($F_{(1,68)} = 9.380$, $p < 0.01$; 1-$\beta = 0.854$).

The power results of 1-β(0.840 among four test conditions and 0.854 between mild and moderate-loss groups) confirm

Table 4. Profiles of ADRO-ALD and SM100 chosen by participants.

	ADRO-ALD		SM100	
Hearing impairment	Medium	Maximum	Moderate	Strong
Mild (*n* = 9)	7	2	4	5
Moderate (*n* = 8)	0	8	0	8

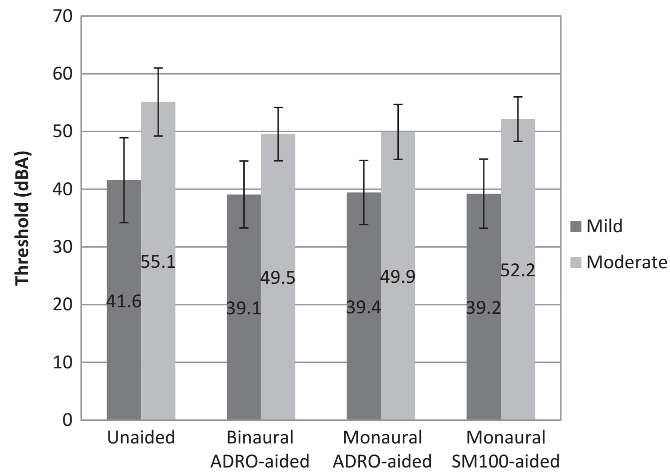

Figure 4. Mean SRTs and standard deviation in quiet (dBA) under unaided, binaurally ADRO-aided, monaurally ADRO-aided, and monaurally SM100-aided conditions.

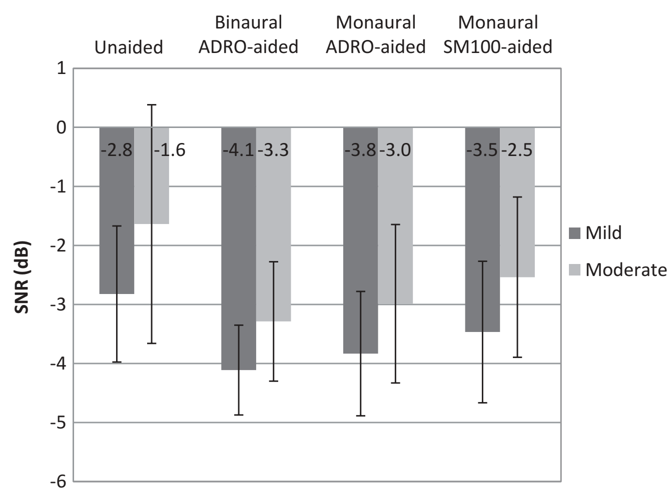

Figure 5. Mean SRTs and standard deviation in noisy environments (dB) under unaided, binaurally ADRO-aided, monaurally ADRO-aided, and monaurally SM100-aided conditions.

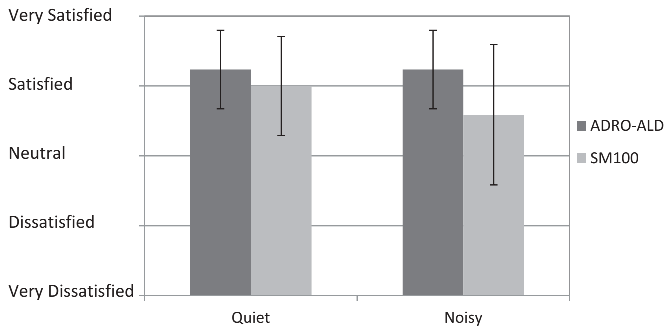

Figure 6. Mean satisfaction ratings and standard deviation of overall speech quality of ADRO-ALD and SM100 in quiet and noisy environments.

the sufficiency of sample size and alleviate concerns of possible increased age related changes, e.g. the hearing processing speed, due to wide age range (21 to 68 years) in response to speech under noise conditions.

Satisfaction ratings in questionnaires

The mean satisfaction in overall speech quality in the quiet and noisy environments is shown in Figure 6. The overall satisfaction ratings demonstrate that all the participants were satisfied with the ADRO-ALD and SM100 in the quiet environments. An ANOVA test indicated no significant difference between ADRO-ALD and SM100 satisfaction in the quiet environment. An additional ANOVA test revealed a significant difference between ADRO-ALD and SM100 satisfaction in the noisy environment ($F_{(1,34)} = 5.026$, $p < 0.05$). No significant difference of mean satisfaction ratings was found between the mild-loss and the moderate-loss groups.

Discussion

In the binaural ADRO-aided quiet environment, the moderate-hearing-loss group received more benefit from ADRO amplification than the mild-hearing-loss group did, regarding MHINT SRT improvement in quiet environments obtained by subtracting the binaural ADRO-aided SRTs from the unaided SRTs in Figure 4 (2.5 dB and 5.6 dB for the mild and the moderate hearing-loss groups, respectively). A similar trend was observed in the SRT improvement in the noisy environments obtained by subtracting the binaural ADRO-aided SRTs from the unaided SRTs in Figure 5 (1.3 dB and 1.7 dB in the SRT improvement, which is equal to 11.7% and 15.3% improvements in speech intelligibility, for the mild and moderate-hearing-loss groups, respectively). These results support the higher correlation in Hartley and colleagues' study on ALD use in the moderate-hearing-loss group than in the mild-hearing-loss group (2010). This is attributable to the mild-loss group having better (lower) initial scores under the unaided condition compared with the moderate-loss group, thus allowing less room for improvement. Chia and colleagues (2007) reported that people with mild hearing loss did not rely on ALDs, because they did not demonstrate more adverse physical or mental performance than did those with standard hearing ability. However, some clinical data show a significant improvement of scores on the APHAB for people with mild hearing loss who used ALD amplification (Yueh et al., 2001).

In the noisy environment, despite the ADRO-aided conditions being significantly improved compared with the unaided conditions (Figure 5), no significant difference was found between monaurally ADRO-aided and binaurally ADRO-aided conditions. Similar performance was observed between monaurally ADRO-aided and binaurally ADRO-aided conditions in the quiet environment (Figure 4). Although the volume setting and amplification profile were maintained the same under both conditions, the benefit of binaural fitting was less than expected. One possible cause is that the good ear was often used under monaurally-aided conditions, thus yielding results that are close to those of the binaurally-aided conditions. Another reason is that nonoccluded ear plugs were used for the ADRO-ALD, which were inefficient at blocking the low-frequency noise, resulting in a similar SNR in the noisy environments.

Regarding the comparison between ADRO and linear amplification schemes used in quiet environments, there was no significant difference in the mean MHINT SRT values among the four test conditions. This is expected because ADRO follows the audibility rule when the sounds are below the audibility target of more than 30% of the time under the quiet condition, which is similar to a linear manner. In the noisy environment, as Figure 5 shows, the SRT in the monaurally ADRO-aided condition was significantly different from that of the unaided condition, whereas the SM100-aided SRT did not differ significantly from the data of the unaided condition. The benchmark results of the SM100 show that the ADRO scheme not only benefits people who experience mild or moderate hearing loss in quiet environments, but is also effectively beneficial in noisy environments. The superior benefit under noisy conditions is attributable to the "background noise rule" of the ADRO, which ensures that background noise is not over-amplified to a level that reduces speech intelligibility.

The overall satisfaction ratings reveal that the participants were satisfied with using both ADRO-ALD and SM100 in the quiet environment. However, in the noisy environment, the participants were more satisfied with the ADRO-ALD than they were with the SM100. The satisfaction results were in agreement with the MHINT data, indicating that the ADRO amplification scheme effectively provided more benefit than the linear scheme in the noisy environment.

The ADRO amplification scheme has been applied in cochlear implants and hearing aids for several decades. This study demonstrated that the ADRO scheme can also be applied to the design of the ALD. The significant cost and fitting time with less benefit than expected contributed to the large percentage of hearing aid owners not using their hearing aids (Hartley et al., 2010). The ADRO-ALD is an affordable and beneficial solution for people with mild or moderate hearing loss before they are fitted with hearing aids. Future studies should consider fitting a remote microphone to a body-worn ALD to compare the difference in benefits between the ADRO and linear amplification designs of a Bluetooth connection. This technology can be further studied on people who experience auditory processing disorder, attention deficit hyperactivity disorder, learning disabilities, or chronic suppurative otitis media in future research.

Conclusion

This study compared the benefits of ADRO and linear amplification strategies implemented in a body-worn device in quiet and noisy environments using MHINT scores and participants' satisfaction as objective and subjective results. The MHINT SRT results for quiet environments show no significant difference among unaided, binaurally ADRO-aided, monaurally ADRO-aided, and monaurally SM100-aided conditions. In noisy environments, the ADRO system demonstrated a significant difference between monaurally aided and unaided conditions, whereas the linear system did not. For both quiet and noisy environments, the moderate-loss group benefited more from ALD amplification than the mild-loss group did, which supported more ALD use in the moderate-hearing-loss group than in the mild-hearing-loss group. The benchmark results show that the ADRO scheme is effectively beneficial to people experiencing mild or moderate hearing loss in noisy environments.

The mean of the satisfaction ratings indicate that the participants were satisfied with the overall speech quality of both ADRO and linear schemes in quiet environments. However, in noisy environments, the participants were more satisfied with the ADRO amplification scheme than with the linear scheme. The satisfaction results are in agreement with the MHINT data—indicating that the ADRO scheme effectively provided more benefit than the linear scheme in noisy environments. These results demonstrate the effective benefits of the ADRO amplification scheme incorporated into an ALD by people who experience mild or moderate hearing loss.

Acknowledgments

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Appendix

QuestionnaireName:____________________ Date:______________

We are interested in your comments on the performance of the assistive listening device in quiet and noisy situations. Please provide answers to the questionnaire that best reflect your experiences. Please feel free to expand on your answers if there is anything else about the device that you think we should know. Your feedback will help us make improvements to the device. Thank you for your time.

Please indicate whether you agree with the following descriptions of the Assistive Listening Device.

	Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied
Sounds become clearer	□	□	□	□	□
Improves listening in noise	□	□	□	□	□

Thank you