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Speech recognition in noise using bilateral open-fit hearing aids: The limited benefit of directional microphones and noise reduction

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Abstract

Objective: To investigate speech recognition performance in noise with bilateral open-fit hearing aids and as reference also with closed earmolds, in omnidirectional mode, directional mode, and directional mode in conjunction with noise reduction. *Design:* A within-subject design with repeated measures across conditions was used. Speech recognition thresholds in noise were obtained for the different conditions. *Study sample:* Twenty adults without prior experience with hearing aids. All had symmetric sensorineural mild hearing loss in the lower frequencies and moderate to severe hearing loss in the higher frequencies. *Results:* Speech recognition performance in noise was not significantly better with an omnidirectional microphone compared to unaided, whereas performance was significantly better with a directional microphone (1.6 dB with open fitting and 4.4 dB with closed earmold) compared to unaided. With open fitting, no significant additional advantage was obtained by combining the directional microphone with a noise reduction algorithm, but with closed earmolds a significant additional advantage of 0.8 dB was obtained. *Conclusions:* The significant, though limited, advantage of directional microphones and the absence of additional significant improvement by a noise reduction algorithm should be considered when fitting open-fit hearing aids.

Key Words: Directional benefit; directional microphone; hearing aid; IOI-HA; Noise reduction; omnidirectional microphone; open fitting

In recent years many hearing-aid manufacturers have introduced open-fit hearing aids (HAs). This technology has been developed to reduce or eliminate the occlusion effect and improve sound quality for people with relatively normal hearing in the lower frequencies. At present, open fittings constitute a considerable and increasing number of all HA fittings. Therefore, it is important to consider possible limitations of this fitting method and to be aware when a traditional fitting with a more closed earmold would be the better choice.

Most open-fit HAs, like other modern HAs, are equipped with directional microphones, which could improve speech recognition in noise relative to performance with an omnidirectional microphone. Previous studies have reported a significantly enhanced signal-to-noise ratio can be achieved by using directional microphones (e.g. Hawkins & Yacullo, 1984; Valente et al, 1995; Ricketts & Dahr, 1999; Ricketts et al, 2003). However, large earmold vents might reduce the advantage of using directional microphones. Directional benefit may be assessed either by electroacoustical measurements or psychoacoustically as the difference between speech recognition thresholds in noise for omnidirectional and directional microphone modes. Ricketts (2000a) evaluated the impact of venting (1 mm, 2 mm, and open) on electroacoustically measured directivity for different hearing aids and

reported that vents decreased the directivity index (DI) of directional HAs in the low-frequency region. Directivity at 500 Hz decreased significantly with vent size from 4.2 dB with a closed earmold to 1.9 dB with a 2 mm vent and − 2.0 dB with an open earmold. There was also a statistically significant DI reduction of about 1 dB at 1000 Hz for all the venting conditions. The overall differences between DIs for the omnidirectional and directional modes (i.e. directional benefit) were 5.6 dB with closed earmold and 4.0 dB with open earmold. This implies that an open fitting may impair the acoustic conditions for directional microphones. In addition, patients intended for an open fitting have close to normal hearing in the lower frequencies, and hence will receive little or no low-frequency amplification, which limits the efficacy of any sound processing in this frequency range. Although directional microphones might still provide front-to-back separation in the higher frequencies, the expected improvements of using directional microphones in open-fit HAs can be questioned. Valente and Mispagel (2008) examined differences between unaided and aided performance in omnidirectional and directional modes using open-fit behind-the-ear HAs. Twenty-six subjects without prior HA experience were fit bilaterally with open-fit HAs in which the receiver unit were placed in the subjects' ear canal. The hearing

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Abbreviations	
ANOVA	Analysis of variance
DI	Directivity index
HA	Hearing aid
HINT	Hearing in noise test
IOI-HA	International outcome inventory for hearing aids
NR	Noise reduction
PB	Phonemically balanced
SD	Standard deviation
SRT	Speech recognition threshold

in noise test (HINT) (Nilsson et al, 1994) was used to determine speech recognition thresholds (SRTs) in noise. The speech material was presented from the front, and the competing noise (R-Space™ restaurant noise) was presented via eight loudspeakers positioned 45° apart at a constant overall summed level of 65 dBA. Comparison of the omnidirectional and directional results revealed a statistically significant mean directional benefit of 1.9 dB. There was also a statistically significant mean advantage of 1.7 dB for the directional condition compared with the unaided condition. No statistically significant difference was noted between the omnidirectional aided and the unaided mean SRTs. Comparing these results with results of studies using similar loudspeaker arrangements and traditional earmold fitting (e.g. Pumford et al, 2000; Ricketts, 2000b) suggest that the open-fit approach would, to some extent, reduce the benefit provided by directional microphones.

A lot of HAs today can be programmed with the combination of a directional microphone and a noise reduction (NR) algorithm. NR refers to the ability of the HA to determine if signals are speech-like or noise-like and make adjustments in the output of the specific frequency region. The goal is to reduce amplification in specific bands when steady-state signals (e.g. background noise) are detected. However, the efficacy of typical NR algorithms is not clear. Several studies have shown subjective benefit of using NR algorithms but no objective benefit as measured with speech recognition tests (e.g. Boymans & Dreschler, 2000; Alcantara et al, 2003; Ricketts & Hornsby, 2005). This is probably due to the fact that the competing noise often has the same spectral shape as the speech signal. Hence, a typical NR algorithm cannot actually improve the signal-to-noise ratio but will reduce the gain in those frequency bands that are less important for speech intelligibility. However, some studies have reported significant improvements of specific NR algorithms on objectively measured speech recognition in noise. Peeters et al (2009) evaluated speech intelligibility in noise offered by a commercial HA using a fully adaptive directional microphone and a NR algorithm that performed gain reductions based on interactive calculation of the resulting speech intelligibility index (SII). Eighteen subjects with varying configurations of sensorineural hearing loss were fit with binaural in-the-canal HAs (N = 10) or open-fit behind-the-ear HAs (N = 8). Speech recognition thresholds were obtained with HINT sentences in four HA conditions; omnidirectional, omnidirectional with NR, directional, and directional with NR. Speech material was presented directly in front of the subjects and noise was presented from three loudspeakers placed at 90°, 180°, and 270°. Results revealed an average directional benefit of 4 dB. Activating the NR improved the HINT results by 2.5 dB in combination with an omnidirectional microphone but only by 0.6 dB (statistically non-significant) with a directional microphone. According to the authors, the limited benefit of NR in directional mode was probably due to the fact that the signal reaching the

HA processor from the directional microphone would be lower and at a better signal-to-noise ratio. The results were not evaluated regarding possible differences between the open-fit behind-the-ear HAs and the in-the-canal HAs. Kuk et al (2005) evaluated the efficacy of an open-fit HA by comparing four combinations of NR (on and off) and microphone modes (omnidirectional and adaptive directional) in eight subjects with open-fit HAs. Speech recognition performance was obtained with HINT sentences for the different conditions. Also in this study, speech was presented directly in front of the subjects and noise was presented from three loudspeakers placed at 90°, 180°, and 270°. The results revealed no statistically significant improvement with the omnidirectional microphone mode compared with unaided when NR was not activated. However, statistically significant improvements were reported for the adaptive directional microphone mode with and without NR. The NR algorithm improved the mean SRT by 0.8 dB, when used in combination with an omnidirectional or directional microphone.

Results of previous studies suggest that real-world benefit of directional microphones and NR algorithms depends on several additive and non-additive factors such as: type of HA, NR approach, noise spectrum, noise source position, reverberation, and interaction between noise management features. Particularly, the influence of open fitting on the efficacy of directional microphones combined with NR algorithms is not yet well established. The few reports are difficult to interpret and compare due to differences in test design (e.g. subjects, HA type, speech, and noise materials, and loudspeaker arrangements). To determining the specific effect of open fitting on the benefit provided by a directional microphone combined with a NR algorithm, direct comparisons between open and closed fittings are required. To the best of our knowledge, no study has previously been published that evaluates microphone modes and NR algorithms for an open fitting in comparison with a traditional earmold fitting for the same subjects and HAs. The primary purpose of the present study was to investigate speech recognition performance in noise with HAs using a routinely applied open fitting and as reference also with a closed earmold for three different sound processing modes: (1) omnidirectional mode, (2) directional mode, and (3) directional mode in conjunction with NR. A secondary purpose was to evaluate the subjective HA benefit for a typical group of new open-fit HA users.

The following specific questions were addressed:

1. Do open-fit HAs with an omnidirectional microphone enhance speech recognition in noise compared to unaided performance?
2. Do directional microphones improve speech recognition in noise in comparison with omnidirectional microphones for open-fit HAs?
3. Does a NR algorithm used in conjunction with a directional microphone further improve speech recognition in noise with open-fit HAs?
4. To what extent might an open fitting reduce the benefit of directional microphones and NR algorithms in comparison with a closed earmold fitting?
5. How do subjective HA outcomes of typical open-fit HA recipients compare to outcomes of the average HA user?

Methods

Subjects

Twenty people (10 males and 10 females), between 51 and 64 years of age (mean: 57.3 years) without prior HA experience, participated in this study. Considering the known variability in speech test results,

this sample size was estimated to be sufficient for detecting clinically significant differences between conditions. The subjects were all on the waiting list for aural rehabilitation, and were recruited based on the following criteria: between the ages of 20 and 65 years, Swedish as first language, symmetric sensorineural hearing loss with pure-tone thresholds of 30 dB HL or better from 250 to 1000 Hz, and 80 dB HL or better from 2000 to 8000 Hz, speech recognition scores with Swedish phonemically balanced (SPB) words in noise (Magnusson, 1995) within the predicted range based on high-frequency pure-tone thresholds and age (Barrenas & Wikstrom, 2000). Table 1 summarizes the pure-tone thresholds for both ears of the 20 subjects. The study was approved by the local ethics committee. The subjects provided their informed consents and were not paid for their participation.

Hearing aid
The HA used was the Phonak Exélia Art M, which can be programmed as an open or closed fitting. This HA has 20 frequency bands that can be individually adjusted. Each subject was fit bilaterally, with one pair of HAs in an open condition with thin tubes and open domes, and with another pair of HAs in a closed condition using unvented shell molds made of acrylic material. The HAs were programmed based on the audiometric configuration of each subject and the fitting approach (open or closed) using a "first fit" with the Phonak adaptive digital formula. Phonak recommends using this prescription formula "rather than distinct separate fitting formulas". The fitting formula is protected by a patent, but a description provided by the manufacturer is presented in the Appendix. The fittings were performed in accordance with local clinical routine for fitting this type of HA. That is, the manufacturer's fitting formula was used and no real ear measurements were performed. Separate programs were made for the three processing modes: (1) omnidirectional microphone mode, (2) directional microphone mode, and (3) directional microphone mode in conjunction with NR. A fixed supercardioid polar pattern was chosen in the directional modes. The level of NR (weak, moderate, or strong) was set to moderate. According to information from Phonak, their NR algorithm is based on the signal-to-noise ratio in the specific channel where the noise appears, and the moderate setting provides an improved speech-to-noise ratio for speech in speech-shaped unmodulated noise of 2 dB at a 0 dB signal-to-noise ratio and 4 dB at a −5 dB signal-to-noise ratio. The HAs were not fine-tuned until data collection was finished.

Speech recognition test
The Swedish speech test material, Hagerman's sentences (Hagerman, 1982), was used to determine SRTs in noise. This test was originally developed in Swedish but is now available in several other languages. Each of the eleven lists in this test material consists of ten sentences with five words. All sentences have the same structure: name –

verb – numeral – adjective – noun (e.g. "Peter has four black baskets"). Hagerman (1982) developed this test material by recording one original list with a female speaker, and then he compiled the various lists by combining the words differently between the sentences. Because all lists comprise exactly the same 50 recorded words, high test-retest reliability is achieved. According to Hagerman and Kinnefors (1995) the standard deviation of repeated measurements is 0.44 dB including the learning effect. Another advantage of these low-predictability sentences is that the lists can be used repeatedly with the same subject, because it is almost impossible to learn the lists by heart (Wagener et al, 2003). Hagerman's sentence material is used in conjunction with a specific masker (i.e. noise signal) that has the same long-term spectrum as the speech signal. The masker is available in a slightly (10%) and a fully (100%) amplitude modulated version. In the present study, the slightly modulated version was used in order to activate the NR algorithm in the HAs.

Speech tests were performed in an audiometric test room at Sahlgrenska University Hospital. The speech and noise materials were played from a CD-player (Philips CD620) connected to an audiometer (Interacoustics AC30) that was calibrated according to ISO-389. The subject was seated in the middle of the room facing a loudspeaker that presented the speech signal. The noise signal was routed through an Interacoustics Directional Hearing Evaluator DHA8 and presented uncorrelated via four other loudspeakers positioned at 45°, 135°, 225°, and 315° around the subject. All the loudspeakers were of the same model, Bose interaudio 1000XL, and were positioned at the height of the subject's head at a distance of 1 m. Calibration of the signals was performed in the test position (i.e. a point corresponding to the center of the subject's head).

The sentences were presented at a fixed level of 65 dB SPL, and the level of the competing noise was adapted according to the method described by Hagerman and Kinnefors (1995). The noise level was initially set at 45 dB SPL and was increased in 5-dB steps until two words or less was repeated correctly. Thereafter, the noise was adjusted in 1-, 2- or 3-dB steps according to the adaptive stepping scheme outlined in Table 2. This stepping scheme will give an SRT that converges at a speech-to-noise ratio corresponding to 40% correct. One list takes less than two minutes to complete.

Follow-up questionnaire
Four to six weeks after completing the experimental part of the study, the benefit of the subjects' open-fit HAs was subjectively determined with the international outcome inventory for hearing aids (IOI-HA). This questionnaire, which originally was developed in English (Cox et al, 2000), has been translated to several other languages, including Swedish (Cox et al, 2002). Psychometric properties of the Swedish version have recently been determined (Brannstrom & Wennerstrom, 2010). IOI-HA comprises seven questions, each assessing a different self-report outcome dimension. These dimensions are: (1) daily use, (2) increased activity, (3) residual activity limitation, (4) satisfaction, (5) residual participation restriction, (6) impact on others, and (7) quality of life. Each question has five different response choices, from 1 (worst) to 5 (best), which always proceed from the worst

Table 1. Mean, standard deviation (SD), minimum, and maximum values of the hearing threshold levels for the 20 subjects; results for the right and left ears are combined.

Frequency (Hz)	250	500	1000	2000	3000	4000	6000	8000
Mean (dB HL)	14.5	16.3	20.1	35.6	42.5	48.6	53.2	57.1
SD (dB)	7.8	9.0	8.4	10.1	8.8	8.5	12.3	14.2
Minimum (dB HL)	0	0	0	10	25	30	20	30
Maximum (dB HL)	30	30	30	60	60	70	80	80

Table 2. The adaptive stepping scheme used for Hagerman's speech test (Hagerman & Kinnefors, 1995).

Number of correctly repeated words	0	1	2	3	4	5
Change of noise level (dB)	−2	−1	0	+1	+2	+3

outcome on the left side to the best outcome on the right side of the form.

Procedure

The present study comprised three appointments spaced 4 to 6 weeks apart. At the first session ear impressions were made for the ear-molds, and subsequently the unaided SRT in noise was obtained with Hagerman's sentences using two scoring lists (20 sentences) preceded by a practice list to find the starting level for the noise. The subjects were informed that the sentences would consist of five words and that the noise level would vary, which makes it sometimes hard and sometimes easy to perceive the sentences. The subjects were instructed to guess when they could not clearly perceive the spoken words.

At the second session, four to six weeks later, two binaural HA fittings were carried out, one open fitting and one with closed ear-molds. After each fitting, the SRTs in noise were obtained for the three processing modes: (1) omnidirectional microphone mode, (2) directional microphone mode, and (3) directional microphone mode in conjunction with NR. In order to avoid learning effects, every other subject started with open fitting and the others started with closed earmolds, and the sequence of the three processing modes was counterbalanced across the subjects according to a cyclic permutation. After an initial practice list, SRTs were determined using two lists (20 sentences) for each condition and microphone mode. Thus, each subject had to listen to 13 lists at the second session. Pauses were taken when changing between the open-fit HAs and those with earmold. After completing the speech recognition tests, the subjects went home with the open-fit HAs and four selectable programs: (1) "Soundflow", (2) omnidirectional mode, (3) directional mode, and (4) directional mode in conjunction with NR. "Soundflow" is the standard adaptive program in the Phonak Exelia M, which adapts automatically to environments such as quiet, speech in noise, comfort in noise, and music.

At the third session, another four to six weeks later, subjects evaluated if they wanted to continue to use these HAs, fine tune the HAs, test other HAs or discontinue using HAs. The IOI-HA questionnaire was also completed at the third session to assess subjective benefit of the open-fit HAs.

Results

Speech recognition thresholds

Figure 1 shows the means and standard deviations (SD) of the SRTs obtained for the different conditions and microphone modes. Because the SRTs are expressed as speech-to-noise ratios, a lower (more negative) SRT indicates better performance. The mean unaided SRT was -6.0 dB (SD = 2.0 dB). With open-fit HAs, the mean SRTs were: -6.3 dB (SD = 1.5 dB) in omnidirectional mode, -7.6 dB (SD = 1.3 dB) in directional mode, and -7.9 dB (SD = 1.3 dB) in directional mode in conjunction with NR. The mean SRTs with closed earmolds were: -7.1 dB (SD = 1.2 dB) in omnidirectional mode, -10.4 (SD = 1.4 dB) in directional mode, and -11.2 (SD = 1.3 dB) in directional mode in conjunction with NR.

A two-way repeated measures ANOVA conducted on the SRTs for the aided conditions reveled significant main effects of fitting (open, closed) [$F(1, 19) = 73.9$, $p < 0.001$] and microphone mode (omnidirectional, directional, directional with NR) [$F(1, 19) = 54.9$, $p < 0.001$]. The interaction between fitting and microphone mode was also significant [$F(1, 19) = 29.0$, $p < 0.001$].
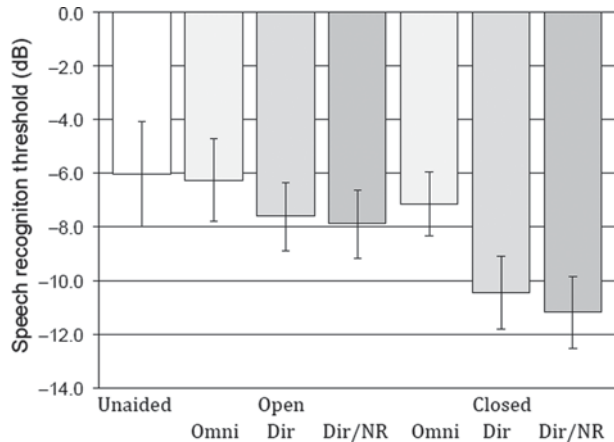
Figure 1. Mean speech recognition threshold (SRT (dB)) in noise for the different listening conditions: unaided, open omnidirectional (Omni), open directional (Dir), open directional with noise reduction (Dir/NR), closed omnidirectional, closed directional and closed directional with noise reduction. Error bars indicate ± 1 SD.

Differences between the mean SRTs for all listening conditions and microphone modes are presented in Table 3. Post-hoc Bonferroni adjusted pairwise comparisons revealed statistically significant differences between most conditions as indicated in Table 3. However, there were no significant differences between the unaided SRTs and the SRTs obtained using HAs with an omnidirectional microphone, regardless if the fittings were open or closed. Using open-fit HAs with directional microphones yielded a 1.6 dB significantly better SRT than unaided ($p = 0.01$). The directional mode yielded significantly better SRT than the omnidirectional mode with the open and closed fitting (p-values < 0.001). Activating the NR in directional mode did not provide a significant additional improvement of the SRT when using an open fitting. However, with closed earmolds a 0.8-dB significant additional improvement ($p = 0.004$) was achieved.

Subjective follow-up

The subjective outcome of the open HA fitting for the study subjects was evaluated after one month using the IOI-HA questionnaire. The results presented in Table 4 are based on 18 subjects. One subject discontinued HA use due to problems in the ear canal, and another subject did not complete the questionnaire due to lack of motivation. The total mean score was 28.9 (SD = 4.7). The highest score was obtained on item 6 (i.e. impact on others). For comparison, Table 4 also provides results from a recent psychometric evaluation of the Swedish version of IOI-HA (Brannstrom & Wennerstrom, 2010). On item 1, which reflects daily use, nine subjects reported a usage of more than 8 hours/day, and six subjects reported a usage between 4 and 8 hours/day. None of the 18 subject reported a HA use of less than 1 hour/day. Seventeen of the 20 subjects continued with the actual open-fit HAs after the third visit, one decided to test HAs from another manufacturer, and two decided not to continue with HAs.

Discussion

The primary purpose of this study was to examine speech recognition performance in noise with open-fit HAs in the omnidirectional mode, directional mode, and a combined directional and NR mode.

Table 3. Differences between the SRTs (dB) for combinations of the unaided, open and closed conditions, and the omnidirectional (Omni), directional (Dir), and directional + noise reduction (Dir + NR) modes. The levels of statistical significance for the differences are marked with stars.

Condition	Unaided	Open/Omni	Open/Dir	Open/Dir + NR	Closed/Omni	Closed/Dir
Open/Omni	0.22					
Open/Dir	1.57**	1.35***				
Open/Dir+NR	1.84**	1.63***	0.27			
Closed/Omni	1.10	0.89	0.47	0.74		
Closed/Dir	4.38***	4.17***	2.81***	2.54***	3.28***	
Closed/Dir+NR	5.14***	4.92***	3.57***	3.30***	4.04***	0.76**

$^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

To facilitate interpretation of the results and enable further comparisons between conditions, reference SRTs were also obtained with closed earmolds and unaided. The results revealed a significant improvement of speech recognition in noise when using directional microphones compared with omnidirectional. However, the directional advantage was on average 1.9 dB smaller for the open fittings compared with closed. Activating the NR feature yielded a significant additional improvement, but only with closed earmolds. Compared with unaided, there was no significant advantage of using HAs with omnidirectional microphones in background noise, neither with open nor with closed fitting.

The test subjects had no prior experience with HAs, and SRTs were obtained for all conditions without any time for adapting to the HAs. An acute testing procedure was considered appropriate, because more acclimatization to some of the test conditions would have put those conditions in favor. Thus, all tested conditions, except the unaided, represented unfamiliar listening situations for all subjects. The study was conducted using one specific HA model (Phonak Exélia Art M) and the fittings were performed using the Phonak adaptive digital formula. This HA is suitable both for open fitting and for fitting with a traditional earmold. To further minimize variations of different parameters in the study, no fine-tuning of the HAs were made before the data collection was completed. It is important to consider that one HA model was used and fittings were performed in accordance with local clinical routine using the actual manufacturer's fitting formula without any real-ear measurements. Thus, the fittings may not have been optimal for all subjects and conditions. However, according to a comprehensive field study reported by Phonak, final settings preferred by users did not differ by more than 3–4 dB in single channels and on average only by 1–2 dB from the settings prescribed by the Phonak adaptive digital formula (Hessefort, 2010). When fitting the actual HA, like many other HAs, an adaptive directional microphone mode is commonly selected; this means that the microphone adapts its directionality depending on where the noise is coming from. However, in this study noise was presented with equal levels from four loudspeakers around the subject. Therefore, a fixed frontal supercardioid polar pattern was used

to avoid random changes of polar pattern throughout the data collection, which in turn could have affected the reliability of the results.

When generalizing laboratory test results to real-world situations, valid test materials and methods are needed. However, for the current purpose of making relative comparisons between conditions, high test-retest reliability was considered more important than maximal ecologic validity. Reliability of speech recognition tests can be expressed as the SD for repeated measurements. The reported normative (i.e. for normal-hearing subjects) SDs for repeated measurements are 0.44 dB for Hagerman's sentences (Hagerman & Kinnefors, 1995), and 0.96 dB for the Swedish HINT (Hallgren et al, 2006). Therefore, we used Hagerman's sentences, although these sentences are somewhat unnatural in comparison with everyday sentences such as the HINT sentences.

The present results revealed SRTs that ranged between −6.0 and −11.2 dB for the different conditions and fitting methods. The relationship between the SRTs for the unaided, the omnidirectional, and directional open-fit conditions were in good agreement with those obtained in the Valente and Mispagel (2008) study. The average directional advantage with open fittings in the current study was 1.4 dB, which is slightly lower than the advantage of 1.9 dB reported by Valente and Mispagel (2008) who used a more difficult listening environment with noise from eight loudspeakers from the front, sides, and behind. In the current study noise was presented from four loudspeakers equally spaced around the subject, but not directly from the front. One might expect greater advantage of directional microphones when less noise is presented from the front; however this situation is also favorable to the omnidirectional microphone mode because of the negative directionality of behind-the-ear HAs in omnidirectional mode (e.g. Ricketts, 2000a). There might also have been differences in openness, because Valente and Mispagel (2008) used HAs with the receiver placed in the ear canal, while thin tubes and domes were used in the current study. There are very few other publications reporting on the magnitude of directional benefit of open-fit HAs. Flynn (2004) presented a study with 49 experienced HA users, of whom 38 were using in-the-ear HAs with an average vent size of 2.3 mm, and 11 were using behind-the-ear HAs with an

Table 4. Mean results (with standard deviation within parentheses) of the IOI-HA questionnaire. The items reflect the following domains: (1) daily use, (2) increased activity, (3) residual activity limitation, (4) satisfaction, (5) residual participation restriction, (6) impact on significant others, and (7) quality of life. Reference values are for a Swedish validation of IOI-HA (Brannstrom & Wennerstrom, 2010).

Item number	1	2	3	4	5	6	7
Present study	4.2 (0.8)	4.1 (1.2)	3.8 (0.9)	4.2 (1.1)	4.3 (0.9)	4.6 (0.6)	3.8 (1.0)
Reference	3.9 (1.1)	4.0 (1.1)	3.5 (1.2)	4.3 (1.0)	4.1 (1.1)	3.9 (1.1)	3.8 (1.0)

average vent size of 3.9 mm. SRTs were obtained with the Danish version of Hagerman's sentences denoted DANTALE II (Wagener et al, 2003). The speech signal was presented from the front, while noise was presented via four loudspeakers located behind the subject at 120°, 150°, 210°, and 240°. Flynn reported a significant mean directional benefit of 3.1 dB. Kuk et al (2005) presented results from eight subjects using open-fit behind-the-ear HAs. The subjects were tested with HINT sentences presented from the front, and noise presented at 90°, 180° and 270°. The results indicated a directional benefit of 1.8 dB. Thus, the directional benefit with open-fit HAs seems not to exceed 2 dB in situations where noise is presented from all directions. The markedly higher benefit reported by Flynn (2004), was probably due to the fact that the fittings were not completely open and the noise signal was only presented from behind.

Regardless of open or closed fitting, the effect of directional microphones might differ between HA manufacturers, HA models, and even the microphone position, because the DI can decrease if the alignment angle varies by more than 10 to 15° in the horizontal plane (Ricketts et al, 2003). In addition, results of laboratory tests are influenced by differences in test procedures. The results of previous studies, in which the researchers have used similar speech test materials and loudspeaker arrangements for estimating directional benefit with traditionally fitted HAs, range from 2.0 to 4.9 dB (e.g. Ricketts, 2000a; Ricketts & Mueller, 2000; Bentler et al, 2004). Thus, open fittings probably reduce directional advantage to some extent compared with earmold fittings. The current study was design to enable direct comparison between an open fitting and an earmold fitting for the same subjects and HAs. The mean directional advantage with closed earmolds was 3.3 dB, which is within the range of the previous results mentioned above and 1.9 dB higher than the directional advantage we obtained with an open fitting. Thus, using open fitting can reduce directional benefit of HAs to 40% in comparison with earmold fitting. This knowledge would be helpful especially when counseling people who are close to the border of the open fitting range. The maximum performance of the directional microphones in the present HAs was established with completely closed earmolds. Of course completely closed earmolds would not be a real option for the actual population, but small vents do not materially affect directional advantage (Ricketts & Mueller, 2000). For people needing a more closed fitting because of a significant amount of hearing loss in the low-frequency region, a partially occluding earmold can be connected to the thin tube. In recent years hollow earmolds have become popular in combination with thin-tube fitting. An advantage of hollow earmolds is that that similar vent effects can be achieved with a smaller vent diameter in comparison with a solid earmold (Kuk et al, 2009). However, studies are needed to evaluate possible differences between hollow and solid earmolds regarding the effect of directional microphones and NR algorithms.

The other main objective of this study was to assess the benefit provided by the HA's NR algorithm when used in combination with the directional microphone. It is important to validate this combination in open-fit HAs, given that most manufacturers recommend using a directional microphone and NR in the same program. As mentioned in the introduction, Kuk et al (2005) reported that a NR algorithm improved the mean SRT by 0.8 dB, when used in combination with an omnidirectional or directional microphone in open-fit HAs. The present results showed a 0.3 dB non-significant additional improvement of NR when using an open fitting, but with closed earmolds a statistically significant advantage of 0.8 dB was obtained. There might be considerable differences in NR between HA brands and models, due to differences in sound

processing and implementation of NR algorithms. For the HAs in this study, we used the middle (denoted moderate) of three selectable levels of the NR, and possibly, the highest level would have generated greater improvement. However, according to data provided by Phonak, the moderate setting should improve SRTs by about 4 dB using unmodulated speech-shaped noise at speech-to-noise ratios around -5 dB. Hagerman's noise, which was used in the current study, is speech-shaped but also slightly (10%) modulated. Possibly, this slight modulation would have caused the NR algorithm not to activate. However, it did activate because there was a significant effect of NR with closed earmolds. It has been shown that a NR algorithm might be less effective when used in combination with a directional microphone. Peeters et al. (2009) reported significant improvement for a NR algorithm when used in combination with an omnidirectional microphone, but little or no improvement in combination with a directional microphone. In the present study the NR was only evaluated in combination with a directional microphone because the manufacturer recommends using this combination. The most probable reason for the small effect of NR in the current study is that the actual speech test material, Hagerman's sentences, has identical frequency spectra for speech and noise, hence there were no specific frequency bands in which more noise could be detected and gain be reduced. Therefore, the low-frequency gain was probably reduced, which provided a small benefit with closed earmolds but not with open fitting where the noise was transmitted directly into the open ear canal. It should be pointed out that a test material with similar speech and noise spectra and a slightly modulated noise signal indeed is valid for the daily challenge of speech recognition in multi-talker surroundings.

The present results, in accordance with previous results (Kuk et al, 2005; Valente & Mispagel, 2008), have shown that people with normal hearing or a mild hearing loss in the low-frequency region and a moderate hearing loss in the high-frequency region will receive benefit from using open-fit HAs with directional microphones in noisy situations. On the contrary, open-fit HAs with omnidirectional microphones do not improve performance compared with the unaided performance in a noisy environment at normal listening levels. Further, the current results suggest that using NR algorithms in combination with directional microphones might not provide additional benefit for open-fit HA users in many common listening situations.

The actual patient population generally has minor difficulty in communicating with others in quiet environments, whereas their hearing problems often become apparent in a noisy situation. Therefore, it is important to give priority to directional mode in open-fit HAs, even though the directional advantage would be smaller than for earmold fittings. Omnidirectional mode could be preferable in some situations, for example, when listening to soft sounds from different directions. However, the efficacy of NR algorithms in combination with omnidirectional microphones needs to be evaluated for open fittings. The present results indicated limited but significant advantages of using open-fit HAs compared with the unaided condition for the actual population, however, users might benefit even more in real life. It is important to consider the limitations of laboratory settings where only one type of speech material, one specific noise signal, one loudspeaker arrangement, and one listening level are being used. It should also be pointed out, that presenting a difference between conditions as a speech-to-noise ratio in dB, which is a more abstract measure than a percentage score, might lead to underrating of the real-world impact. An improved speech-to-noise ratio of 1 dB corresponds to an improved recognition score of up to 25 percentage

points (pp) for Hagerman's sentence test, which has a very steep psychometric function (Hagerman, 1982). Although the slopes of the psychometric functions for speech materials that are comprised by everyday sentences are commonly shallower, e.g. American English HINT (Nilsson et al, 1994): 9.7 pp/dB, and Swedish HINT (Hallgren et al, 2006): 17.9 pp/dB, it is clear that just one dB improvement of the speech-to-noise ratio would make great difference in speech recognition performance.

After finishing the experimental part of the study the subjects went home with their open-fit HAs. At a follow-up appointment four to six weeks later their HA outcomes were subjectively evaluated using the Swedish version of IOI-HA. A psychometric evaluation of the Swedish version of this questionnaire has recently been performed (Brannstrom & Wennerstrom, 2010). This evaluation comprised 224 people with different types of hearing losses and no prior HA experience, who received either unilateral or bilateral HAs. Different kinds of HAs were used: behind the ear, completely in the canal, and open-fit HAs. Six months after the fitting was completed, the subjects evaluated their HAs by completing the IOI-HA questionnaire. The results were in accordance with results obtained with other versions of IOI-HA. The global mean score was 27.7 (SD = 5.2), and the results for each item are presented as reference values in Table 4. The global mean score for the current test subjects after 4–6 weeks with open-fit HAs was 28.9 (SD = 4.7). The scores on the different items were equal or slightly higher than the scores reported in the evaluation study (Brannstrom & Wennerstrom, 2010). The greatest difference was found on item 6 (impact on others), where the mean score was 4.6 as compared with 3.9. Also, item 1 (usage) yielded a higher mean score in the present study, 4.2 as compared with 3.9. The short period of time before administering the questionnaire (i.e. 1 month vs. 6 months) could have influenced the results. However, IOI-HA scores have shown to be quite stabile over time (Vestergaard, 2006). Thus the results indicate that the present subjects, despite only mild to moderate hearing loss, were on average at least as satisfied with their HAs as are most HA users.

Conclusions

The present results confirm that open fitting significantly reduces the possible benefit of directional microphones and NR algorithms in HAs. More studies are needed to further evaluate the efficacy of open-fit HAs and compare different designs, technologies and special algorithms. It is also important to expand our knowledge about the most appropriate fitting method for different audiometric configurations, and establish guidelines for counseling patients to the best choice. Because the unaided performance in noise may not be improved by using open-fit HAs with omnidirectional microphones, it is important to give priority to directional mode in open-fit HAs.

Based on the current results, while also considering previous studies, we make the following specific conclusions regarding HAs for people with normal hearing or a mild hearing loss in the low-frequency region and a moderate to severe hearing loss in the high-frequency region:

1. Using open-fit HAs with omnidirectional microphones do not significantly enhance speech recognition in noise compared to unaided performance.
2. Using open-fit HAs with directional microphones can significantly improve speech recognition in noise compared to unaided and omnidirectional aided performance.
3. Utilizing NR algorithms in combination with directional microphones in open-fit HAs may not further improve speech recognition in noise.
4. Advantages of directional microphones and NR algorithms are significantly reduced by using open fitting compared to conventional earmolds
5. The results of the IOI-HA questionnaire indicate that successful hearing rehabilitation of people with this common type of hearing loss can be achieved by means of open-fit HAs.

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Appendix

Calculation of targets: Phonak Adaptive Digital

Rather than distinct, separate fitting formulas, the hearing instrument uses the Phonak Adaptive Digital fitting formula, which includes transitions for different hearing loss configurations. As such it recognizes configurations such as 'standard', 'ski-slope' 'low-frequency' and 'profound' hearing losses. The Phonak Adaptive Digital fitting formula also recognizes the importance of reaching gain targets at specific frequencies, depending on the hearing loss configuration. For example, the importance of reaching targets for speech-relevant inputs and frequencies (the so-called speech banana) is weighted higher than for frequencies outside this speech banana. The transitions from 'standard' to a different fitting pre-calculation are:

TRANSITION TO SKI-SLOPE CRITERIA

- Hearing thresholds at or below 750 Hz to be less than 30 dB HL.
- Hearing thresholds at 4000 Hz or higher should be at least 50 dB more than hearing thresholds at 500 Hz or lower.

- The slope over two octaves between 500 Hz and 4000 Hz inclusive should be at least 50 dB.

TRANSITION TO LOW-FREQUENCY HEARING LOSS CRITERIA

- Hearing thresholds at or below 750 Hz should be at least 25 dB worse than at 1500 Hz or higher.
- Hearing thresholds between 2000 and 4000 Hz (inclusive) should be 20 dB HL or better.
- Weight shapes are low for regions with hearing loss of more than 45 dB HL over the minimum hearing loss between 500 and 4000 Hz.

TRANSITION TO PROFOUND HEARING LOSS CRITERIA

- Average hearing thresholds at 500, 1000, 2000, and 4000 Hz should be at least 75 dB HL.
- Hearing thresholds should be more than 55 dB HL.