Original Article

Trends in Hearing
Volume 25: 1–15
© The Author(s) 2021
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/23312165211023709
journals.sagepub.com/home/tia
SAGE

Influence of Three Auditory Profiles on Aided Speech Perception in Different Noise Scenarios

Mengfan Wu[1,2,3], Oscar M. Cañete[4], Jesper Hvass Schmidt[1,2,3,5,6], Michal Fereczkowski[1,2,3], and Tobias Neher[1,2,3]

Abstract

Hearing aid (HA) users differ greatly in their speech-in-noise (SIN) outcomes. This could be because the degree to which current HA fittings can address individual listening needs differs across users and listening situations. In two earlier studies, an auditory test battery and a data-driven method were developed for classifying HA candidates into four distinct auditory profiles differing in audiometric hearing loss and suprathreshold hearing abilities. This study explored aided SIN outcome for three of these profiles in different noise scenarios. Thirty-one older habitual HA users and six young normal-hearing listeners participated. Two SIN tasks were administered: a speech recognition task and a "just follow conversation" task requiring the participants to self-adjust the target-speech level. Three noise conditions were tested: stationary speech-shaped noise, speech-shaped babble noise, and speech-shaped babble noise with competing dialogues. Each HA user was fitted with three HAs from different manufacturers using their recommended procedures. Real-ear measurements were performed to document the final gain settings. The results showed that HA users with mild hearing deficits performed better than HA users with pronounced hearing deficits on the speech recognition task but not the just follow conversation task. Moreover, participants with pronounced hearing deficits obtained different SIN outcomes with the tested HAs, which appeared to be related to differences in HA gain. Overall, these findings imply that current proprietary fitting strategies are limited in their ability to ensure good SIN outcomes, especially for users with pronounced hearing deficits, for whom the choice of device seems most consequential.

Keywords

hearing loss, hearing aids, speech perception, noise, individual differences

Received 19 January 2021; Revised 24 April 2021; accepted 12 May 2021

Introduction

Understanding speech in the presence of background noise is a challenging task for older persons with hearing loss (e.g., Humes, 2016; Prosser et al., 1991), and hearing aid (HA) treatment often provides limited benefit in such situations (Hornsby et al., 2006; Woods et al., 2015). As a matter of fact, issues with speech-in-noise (SIN) perception are the main concern of many HA users (Abrams & Kihm, 2015; Mendel, 2007). Therefore, successful HA rehabilitation requires satisfactory improvements in aided SIN outcome. As substantial interindividual variability in aided SIN outcome is a common finding (e.g., Eddins et al., 2013;

[1]Institute of Clinical Research, Faculty of Health Sciences, University of Southern Denmark, Odense, Denmark
[2]Research Unit for ORL—Head & Neck Surgery and Audiology, Odense University Hospital, Odense, Denmark
[3]University of Southern Denmark, Odense, Denmark
[4]Hearing Systems Section, Department of Health Technology, Technical University of Denmark, Lyngby, Denmark
[5]Department of Otolaryngology, Head & Neck Surgery and Audiology, Odense University Hospital, Odense, Denmark
[6]OPEN, Odense Patient data Explorative Network, Odense University Hospital, Odense, Denmark

Corresponding Author:
Mengfan Wu, Institute of Clinical Research, University of Southern Denmark, Campusvej 55, DK-5230 Odense, Denmark.
Email: awu@health.sdu.dk

Lopez-Poveda et al., 2017; Nuesse et al., 2018), gaining a better understanding of the factors underlying this variability is an important step toward improved hearing rehabilitation.

It has been hypothesized that one of the main sources of this variability is the diversity in hearing deficits that accompany reduced hearing sensitivity (as measured by the pure-tone audiogram) and that manifest themselves at suprathreshold levels (Johannesen et al., 2016; Moore, 2021; Plomp, 1978). Suprathreshold hearing deficits can affect binaural, spectral, or temporal processing abilities and usually cannot be predicted from the audiogram (Füllgrabe et al., 2015; Lőcsei et al., 2016). As current HA fitting procedures typically rely on the pure-tone audiogram only, listeners with similar audiograms but different suprathreshold hearing abilities will receive similar HA fittings. This may, at least partly, explain the large variance in aided SIN outcomes reported in the literature.

To better understand the relations between various types of auditory deficits and their influence on HA outcome, an auditory test battery was recently developed in the Better hEAring Rehabilitation (BEAR) project (Sanchez-Lopez et al., 2019). This test battery includes measures of audibility (i.e., pure-tone audiometry), speech perception (i.e., the Danish hearing-in-noise test; Nielsen & Dau, 2011), loudness perception (i.e., adaptive categorical loudness scaling; Brand & Hohmann, 2002), binaural processing abilities (i.e., interaural phase difference sensitivity and binaural pitch detection; Füllgrabe et al., 2017; Santurette & Dau, 2012), and spectro-temporal modulation sensitivity (Bernstein et al., 2016). In addition to this test battery, a data-driven approach was proposed that, based on the test-battery results, allows classifying listeners into four distinct auditory profiles labeled A, B, C, and D (Sanchez-Lopez et al., 2020). Table 1 summarizes the overall relative outcomes of these profiles on the different test-battery measures. As can be seen, Profile-A listeners show good or close-to-normal outcome on all measures. In contrast, Profile-C listeners show poor or clearly abnormal outcome on all measures. Profile-B and Profile-D listeners, in turn, show mixed outcomes.

Differences in hearing abilities are not the only factor influencing SIN outcome. The noise encountered in typical daily-life environments can range from stationary noise with a flat frequency spectrum, through fluctuating noise with spectral characteristics like those of human speech (e.g., multitalker babble) to intelligible speech interferers. Broadly speaking, noise signals like these give rise to two types of masking effects, that is, energetic masking and informational masking (e.g., Kidd et al., 2008; Mattys et al., 2012). Energetic masking occurs when target and masker signals overlap in time and frequency in the auditory periphery (Brungart, 2001). Informational masking occurs at higher levels of auditory processing when there are target and masker signal components that are separated in time and frequency and that resemble each other in terms of their acoustic-linguistic properties, making it difficult for the auditory system to tease them apart (for a review, see Kidd et al., 2008).

In many real-life settings that contain different types of noise signals, normal-hearing (NH) listeners cope consistently well and thus achieve good SIN outcomes (Wong et al., 2012). In comparison, older listeners with hearing impairments generally show SIN perception deficits and larger interindividual differences, particularly in complex listening situations with, for example, traffic noise or interfering speech signals (Lőcsei et al., 2016; Prosser et al., 1991). In addition, they benefit less from amplitude modulations in noise signals (Bacon et al., 1998; George et al., 2006) or from spatial separation of multiple competing signals (Hornsby et al., 2006). These differences are likely due to a reduced ability to process temporal and spatial cues (Arbogast et al., 2005; Johannesen et al., 2016; Kidd et al., 2019; Lőcsei et al., 2016). As pointed out earlier, current HA fittings focus on the pure-tone audiogram and therefore neglect suprathreshold hearing deficits. Thus, it is possible that HA users with certain suprathreshold deficits show particularly poor SIN outcomes in certain noise scenarios, whereas HA users with other hearing deficits can cope

Table 1. Overall Relative Outcomes of the Four Auditory Profiles for the Main Measures From the BEAR Test Battery.

Auditory profile	Audibility LF	Audibility HF	Binaural processing	Loudness perception	Speech perception	Spectro-temporal resolution
A	☺	😐	☺	☺	☺	☺
B	☺	☹	😐	😐	☹	☹
C	☹	☹	☹	☹	☹	☹
D	☹	😐	☺	☹	☺	😐

Note. LF = low frequencies; HF = high frequencies; ☺ = good or close-to-normal outcome; 😐 = somewhat abnormal outcome; ☹ = poor or clearly abnormal outcome.

relatively well in the same situations. As a masker signal becomes more similar to a target-speech signal (and informational masking is thus involved), it becomes generally more difficult for the auditory system to suppress (Rosen et al., 2013). For HA users with severe suprathreshold hearing deficits, noise scenarios with intelligible speech maskers are likely to be more challenging. As the four auditory profiles described earlier capture distinct differences in suprathreshold hearing deficits, it is therefore possible that they interact with different noise types as regards aided SIN outcome.

Apart from hearing abilities and noise types, differences among the hearing devices used by hearing-impaired persons can, potentially, further increase the interindividual variance in aided SIN outcome. In current clinical practice, HAs are commonly fitted according to the manufacturers' proprietary procedures (Anderson et al., 2018). As a result, the HA settings prescribed for a given audiogram may differ across devices (Sanders et al., 2015), and in some cases such differences can be large (Keidser et al., 2003). It is currently unclear to what extent such differences affect SIN outcome, as findings are not consistent across studies (Abrams et al., 2012; Valente et al., 2018).

The purpose of this study was to address the following three research questions: (a) Is there an influence of the auditory profiles on aided SIN outcome? (b) How does the type of background noise affect aided SIN outcome for these profiles? (c) Do current HA fittings as recommended by different manufacturers influence SIN outcome, and if so, are there any interactions with the auditory profiles? To explore these questions, a sentence-recognition task and a just follow conversation (JFC) task involving the self-adjustment of the target-speech level were applied. HA users belonging to different auditory profiles were recruited together with a reference group of NH listeners. Three noise conditions ranging from stationary speech-shaped noise to multitalker babble mixed with intelligible speech dialogues were used. In this way, the degree of speech resemblance was manipulated and its influence on aided outcome for the different profiles investigated. Furthermore, three state-of-the-art HAs were included and fitted according to the manufacturers' recommended procedures. In this manner, it was explored how different HA fittings that are representative of current clinical practice affect SIN outcome more generally, and for the different auditory profiles in particular.

Method

Participants

A group of older, habitual HA users and a group of young NH participants were recruited. The HA users were 31 native Danish participants (11 females) aged 60 to 81 years (mean = 72.1 years, standard deviation [*SD*] = 4.3 years) with at least 2 years of HA experience. Their own HAs were Oticon ($N = 13$), Widex ($N = 9$), GN Resound ($N = 5$), Siemens ($N = 2$), Signia ($N = 1$), or Phonak ($N = 1$) devices. None of them had any experience with any of the HA models tested in this study. Six HA users were tested at Bispebjerg Hospital, Copenhagen, Denmark, while the 25 other HA users were tested at the University of Southern Denmark, Odense, Denmark. Nineteen of the 31 HA users had participated in a previous study as part of which they had been profiled (Wu et al., 2020). The other 12 participants were profiled at the start of this study. The distribution of the auditory profiles was as follows: 9 Profile-A, 12 Profile-B, and 10 Profile-C participants. Generally speaking, Profile-D listeners are rare in the hearing-impaired population as a whole (Sanchez-Lopez et al., 2020). Although considerable efforts were made to include around 10 Profile-D participants in this study, only 4 could be recruited. Given the small group size, they were excluded from the analyses reported later. The NH reference group consisted of six native Danish participants aged 21 to 35 years (mean = 26 years, 2 females) who were all tested at the University of Southern Denmark.

Initially, all participants had their audiograms measured (see Figure 1). The HA users had bilateral, symmetrical sensorineural hearing losses. The range of hearing loss configurations was generally in-between the N1 and N4 standard audiograms of Bisgaard et al. (2010). The air-bone gap and interaural asymmetry in audiometric thresholds from 0.5 to 4 kHz were maximally 10 dB at any test frequency. The pure-tone hearing thresholds of the NH participants did not exceed 20 dB HL at any test frequency. None of the study participants reported a history of any neurological or language disorders.

Test Setup

The measurements were carried out in a large sound-proof booth. An Affinity 2.0 system (Interacoustics, Middelfart, Denmark) was used for the audiometry and real-ear measurements (REM). The stimuli were presented via an RME Fireface UC soundcard and five active loudspeakers (Genelec 8020 D). The participants sat in a chair at the center of the sound field facing the frontal loudspeaker, which played back the target-speech material (Figure 2). The radius of the loudspeaker setup was approximately 1.3 m. The noise was presented via the four remaining loudspeakers surrounding the participant. A touch screen or tablet was used for entering the participants' responses.

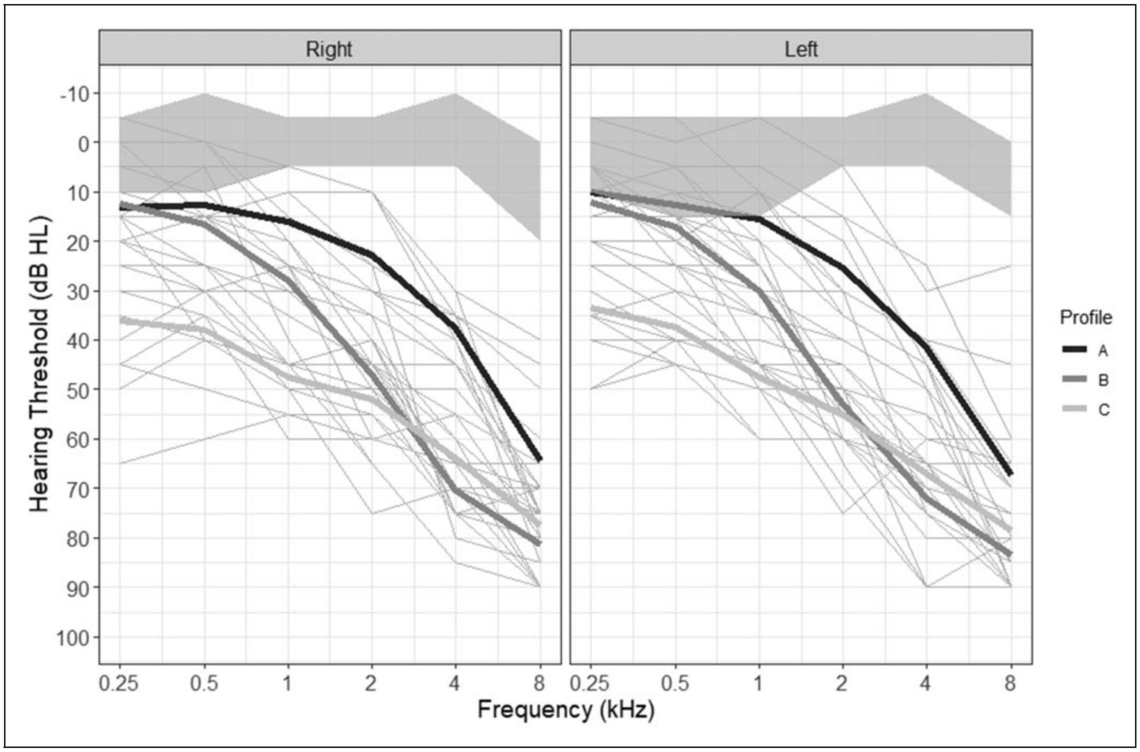

Figure 1. Individual Pure-Tone Audiograms of the 31 HA Users (Thin Gray Lines) and Mean Thresholds of the Three Auditory Profiles (Thick Lines). The gray area shows the range of hearing thresholds of the participants with normal hearing.

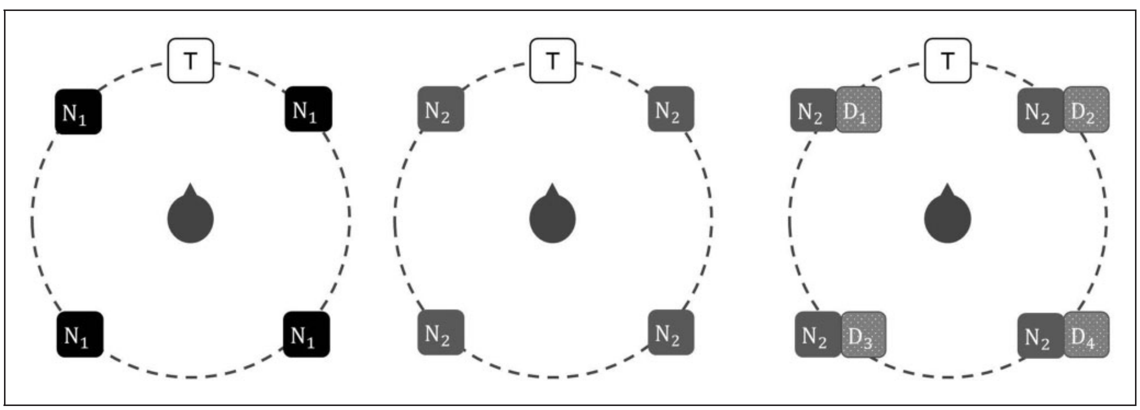

Figure 2. Illustration of the Test Setup With the Target Speech (T) and Three Noise Conditions. N_1: SSN; N_2: BBN; D_1-D4: Mixed-gender dialogues. SSN = speech-shaped noise; BBN = speech-shaped babble noise; BBN+DLGs = BBN with intelligible dialogues.

Stimuli

Target-Speech Material. The target material for the speech-recognition task was the sentence material from the Danish Hearing in Noise Test (HINT; Nielsen & Dau, 2011), which consists of 3 training lists and 10 test lists of 20 sentences each. For the HA-user group, nine of test lists were used, while for the NH group three lists were used. The order of the lists was randomized across all participants.

The target material for the JFC task consisted of three long dialogues of two male speakers recorded by Sørensen et al. (2018). During the recording of these dialogues, the speakers had to carry out a Diapix task (Baker & Hazan, 2011) in a noisy environment. In this study, these dialogues were chosen to recreate a realistic and natural conversation scenario.

Noise Maskers. Three noise signals were used: (a) stationary speech-shaped noise (SSN), (b) speech-shaped babble

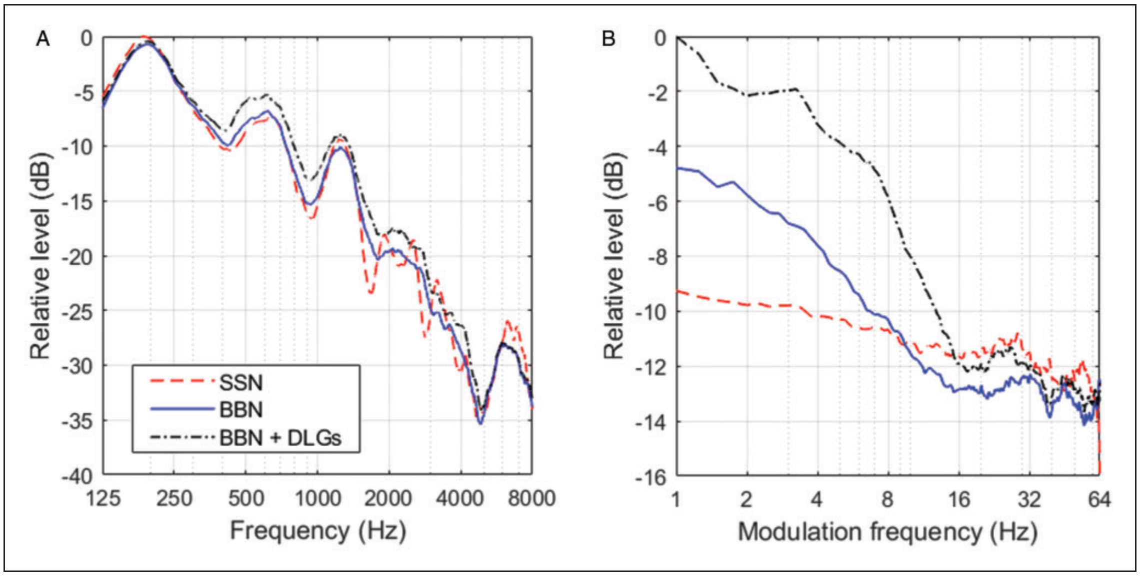

Figure 3. (A) Frequency spectra and (B) modulation spectra of the three noise signals.

noise that was created by mixing a large number of individual speech recordings together (BBN), and (c) BBN with four mixed-gender dialogues also recorded by Sørensen et al. (2018), with each of these dialogues presented from a different loudspeaker (BBN_{+DLGs}). The four mixed-gender dialogues were set to −2.5 dB signal-to-noise ratio (SNR) each with respect to the BBN signal. The SSN and BBN were matched to both the HINT and JFC target-speech materials in terms of their long-term average spectra. As shown in Figure 3, the three noise signals were therefore very similar in terms of their frequency spectra while in terms of their modulation spectra, they differed at low frequencies, with the BBN and especially the BBN_{+DLGs} signal being more modulated than the SSN signal. The noise signals were calibrated to 70 dB (A) SPL at the center of the loudspeaker setup. The order of the three noise conditions was randomized across the participants.

Procedure

For the HA users, there were two to three visits lasting approximately 1.5 to 2 h each. For the NH participants, there was one visit lasting approximately 1 h. At the beginning of the first visit, all participants signed an informed consent form. Next, an otoscopy was carried out and a pure-tone audiogram measured. The HA users then went through the HA fitting process and the REM. At the second visit, the HINT and JFC measurements were carried out. Fourteen HA users repeated these measurements at their third visit. Because a test–retest analysis of their data showed high reliability for both SIN tasks (within-subject SD, SD_w HINT: 0.7 dB SNR; SD_w JFC: 1.05 dB SNR), the remaining HA users completed the HINT and JFC measurements only once and thus came for only two visits.

HA Fittings. Each HA user was fitted with three behind-the-ear HAs (GN LiNX Quattro, Oticon Opn S1 and Widex Evoke 440), which are anonymized in the following sections to comply with the collaboration agreement of the BEAR project. To ensure that the tested HA fittings resembled current clinical practice in Denmark, the default procedure implemented in each manufacturer's fitting software was followed. Thus, the manufacturers' proprietary fitting rules were used. Noncustom domes were chosen based on individual ear-canal sizes and the recommendations made by the fitting software. Fine -tuning was only carried out if the participants experienced discomfort. In that case, the overall HA gain was adjusted. This was necessary once for HA1, four times for HA2 and five times for HA3. In all cases, the overall gain was turned down by a few decibels.

After each fitting, REM was carried out to document the amplification in the ear canals of the HA users. The REM protocol included real-ear unaided gain, real-ear occluded gain, and real-ear insertion gain (REIG) measurements. As the stimulus, the International Speech Test Signal (Holube et al., 2010) was chosen and presented for 20 s at an overall level of 70 dB SPL. For reference purposes, the gain prescription according to the National Acoustic Laboratories-Non-Linear 2 (NAL-

NL2) fitting rule (Keidser et al., 2011) was also calculated for each participant.

HINT Task. For the HINT task, the participants were instructed to repeat the presented sentences as best as they could. An audiologist sitting outside the loudspeaker setup scored their responses. Before the first measurement per noise condition, one training run was carried out to familiarize the participants with the task. Speech-reception thresholds (SRTs) were then measured using the adaptive procedure from the HINT (Nielsen & Dau, 2011). The starting level of the target speech was 72 dB SPL. The level of the noise remained fixed throughout the measurements. For a correct response, the participants were required to repeat the whole sentence correctly. If the response to the first sentence was incorrect, that sentence was repeated with a 4-dB level increase until the response was correct. Afterward, a one-up one-down procedure was used. The step size was 4 dB for the first 4 sentences and 2 dB for the remaining 16 sentences. The SRT was calculated by averaging the SNRs for the 5th to the (hypothetical) 21st sentence.

JFC Task. For the JFC task, the participants were asked to listen to the target dialogue presented via the frontal loudspeaker and to adjust its level using buttons presented on the touch screen or tablet. The following instructions, modified from the ones in (Larsby & Arlinger, 1994), were given to the participants in Danish:

> You are asked to adjust the level of the conversation by the two male speakers, so that you can just understand what is being said. If you find it easy to follow the conversation, the level is too high. If you can't keep up, the level is too low. You need to set the level, so that you can just about comprehend the content of the conversation, even though sometimes you may miss a word or two. Afterwards press "OK."

To ensure the participants understood and were able to complete the task, a training run was carried out initially. The start SNR was randomized between −4 dB and +6 dB. The step size for the level adjustments was 2 dB. The outcome was the mean of five self-adjusted SNRs per test condition. During the measurements, any self-adjusted SNR that deviated by more than ±2.5 dB from the median was considered an outlier. In such a case, an extra run was performed until there were five reliable self-adjusted SNRs per participant.

Statistical Analyses

The statistical analyses were conducted using linear mixed-effects models to assess the effects of auditory profile, noise type, and HA (all fixed effects) on SIN outcome. All analyses were implemented in *R* using the *lmer*() function from the *lme4* package (Bates et al., 2014). The dependent variable was either the SRT (HINT task) or the self-adjusted speech-to-noise ratio (JFC task). Helmet contrast coding was applied to all three categorical variables. The participants were included as random intercepts. The two created models included the Profile × Noise and Profile × HA interactions. Other interactions were excluded because they were not statistically significant. The analyses were carried out as type-III analyses of variance with Satterthwaite's method for estimating the number of degrees of freedom. To investigate the origin of any significant main effects and interactions post hoc analyses based on Tukey adjusted comparisons were conducted.

Results

REM Data

Figure 4 shows mean REIGs for the three tested HAs for profiles A, B, and C together with mean NAL-NL2 gain targets. Compared with the other two HAs, HA2 provided more gain at 500 and especially 1000 Hz. The gains for HA1 and HA3 were very similar for profiles A and B, while for Profile C they differed by about 5 dB at 2000 and 4000 Hz. For Profile C, the REIGs deviated the most, with HA1 (at 2000 and 4000 Hz) and HA2 (at 500 and 1000 Hz) giving more gain than HA3. It is also worth noting that the gains prescribed by the proprietary fitting rationales were mostly higher than those calculated by the NAL-NL2 rule. This is consistent with similar data collected by Sanders et al. (2015) who observed that for a 75-dB SPL input level various proprietary rationales generally prescribed more gain than NAL-NL2 (while for lower input levels, the opposite was generally true).

Speech Recognition Measurements (HINT Task)

Figure 5 shows boxplots of the SRTs of the three profiles (averaged across the three HAs) as well as the NH participants for the three noise conditions. As expected, the NH controls performed better than the HA users in all noise conditions (Wilcoxon rank sum tests, all $p < .001$). Across the three noise conditions, the performance difference between the NH controls and HA users was relatively constant (approximately 3 dB).

Consistent with earlier findings (Wu et al., 2020), the Profile-C HA users had the highest median SRT and the largest variance across individuals. By comparison, the Profile-A HA users had the lowest median SRT as well as the smallest variance, with Profile-B HA users lying in-between. The corresponding mixed-model

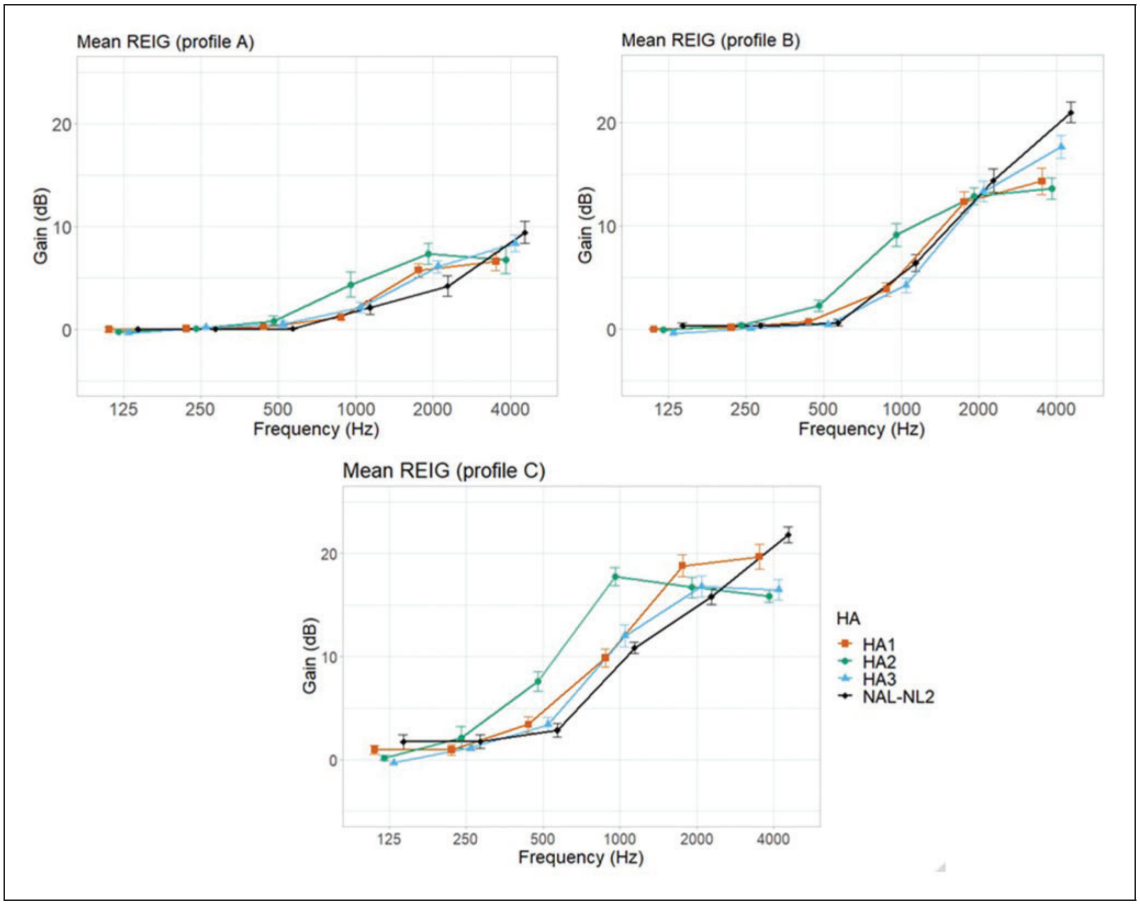

Figure 4. Mean REIGs Measured at 70-dB SPL Input Level for the Three Tested HAs Together With NAL-NL2 Target Gains for Profiles A (Top left), B (top right), and C (bottom). NAL-NL2 target gains are displayed for reference purposes. Error bars represent ±1 standard error of the mean. REIG = real-ear insertion gain; HA = hearing aid; NAL-NL2 = National Acoustic Laboratories-Non-Linear 2.

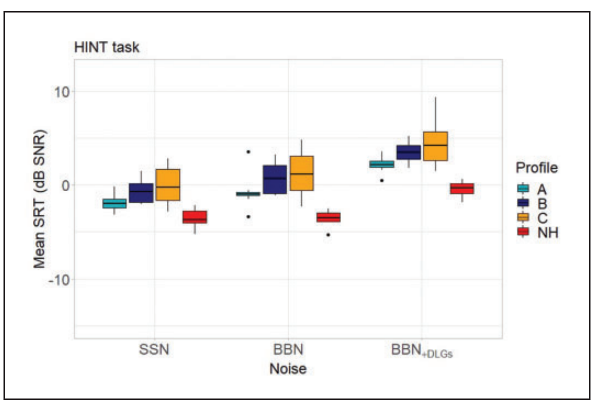

Figure 5. Boxplots of the Mean SRTs for the Three Auditory Profiles and NH Participants in the Three Noise Conditions. For the HA users, the data were averaged across the three HAs. SSN = speech-shaped noise; BBN = speech-shaped babble noise; BBN+DLGs = BBN with intelligible dialogues; SRT = speech-reception threshold; SNR = signal-to-noise ratio; NH = normal-hearing; HINT = Hearing in Noise Test.

analysis (Table 2) showed a main effect of auditory profile, which was due to the difference in mean SRTs between profiles A and C ($\Delta SRT_{A\text{-}C} = -2.1$ dB SNR, $t_{28} = -2.8$, $p = .02$). Moreover, there was a main effect of HA, which was due to the difference in mean SRTs between HA1 and HA3 ($\Delta SRT_{HA1\text{-}HA3} = -0.4$ dB SNR, $t_{236} = -2.5$, $p = .03$) as well as HA2 and HA3 ($\Delta SRT_{HA2\text{-}HA3} = -0.7$ dB SNR, $t_{236} = -4.7$, $p < .001$). In addition, the effect of noise condition was significant, with the mean SRTs for the three noise conditions all differing from each other (all $t_{236} < -7.9$, all $p < .001$).

In addition to the three main effects, there was a significant interaction between HA and auditory profile. Post hoc analyses showed that this was due to the results of the Profile-C participants (Figure 6). Specifically, their mean SRT obtained with HA3 was higher (poorer) than their mean SRTs obtained with HA2 ($\Delta SRT_{C\times HA3\text{-}C\times HA2} = 1.3$ dB SNR, $t_{236} = -4.8$, $p < .001$) or HA1 ($\Delta SRT_{C\times HA3\text{-}C\times HA1} = 1.2$ dB SNR, $t_{236} = -4.3$, $p < .001$). Moreover, when tested with

HA3, the Profile-A participants showed significantly better performance than the Profile-C participants ($\Delta SRT_{A\times HA3\text{-}C\times HA3} = -2.8$ dB SNR, $t_{34} = -3.7$, $p = .02$).

Table 2. Results From the Linear Mixed-Effects Models for the Effects of Auditory Profile, Noise Condition, HA, and the Interactions Profile × Noise as Well as Profile × HA.

		HINT task	JFC task
Profile	*df*1, *df*2	2, 28	2, 27.9
	F	4.1	3
	p	**.03***	.06
Noise	*df*1, *df*2	2, 236	2, 234.9
	F	373.5	517.2
	p	**<.001*****	**<.001*****
HA	*df*1, *df*2	2, 236	2, 234.9
	F	10.9	2.8
	p	**<.001*****	.06
Profile × Noise	*df*1, *df*2	4, 236	4, 234.9
	F	0.9	1.8
	p	.59	.12
Profile × HA	*df*1, *df*2	4, 236	4, 234.9
	F	3.4	2.6
	p	**.009****	**.04***

Note. The analyses were performed on either the SRT data (HINT task) or the self-adjusted speech-to-noise ratios (JFC task). Significant *p* values are shown in boldface. HINT = Danish Hearing in Noise Test; HA = hearing aid; JFC = just follow conversation.
*: $p<.05$, **: $p<.01$, ***: $p<.001$

Self-Adjusted Speech-to-Noise Ratios (JFC Task)

Figure 7 shows boxplots of the mean self-adjusted speech-to-noise ratios of the three profiles (averaged across the three HAs) as well as the NH participants for the three noise conditions. In general, the variance in the JFC data was larger than in the HINT data. As was the case for the HINT data, the NH controls had lower SNRs than the HA-user group for all three noise conditions (Wilcoxon rank sum tests, all $p < .001$). In the SSN condition, the difference between the NH controls and HA-user group was approximately 8 dB, while in the other two noise conditions it was approximately 4 dB.

Regarding the HA-user group, profiles A and C showed a larger variance across individuals than Profile B. While there was a tendency for Profile-C HA users to have higher self-adjusted speech-to-noise ratios than Profile-A and Profile-B HA users, no effect of auditory profile was found (Table 2). The same was true for HA. The effect of noise condition, however, was significant, with the mean self-adjusted SNRs for the three noise conditions all differing significantly from each other (all $t_{235} < -10.8$, all $p < .001$). Furthermore, the interaction between HA and auditory profile was significant. Post hoc analyses showed that this was due to the Profile-C participants having a significantly higher mean self-adjusted SNR with HA3 compared with HA2 ($\Delta SNR_{C\times HA2\text{-}C\times HA3} = -1.3$ dB, $t = -3.6$, $p = .01$), as also apparent from Figure 8.

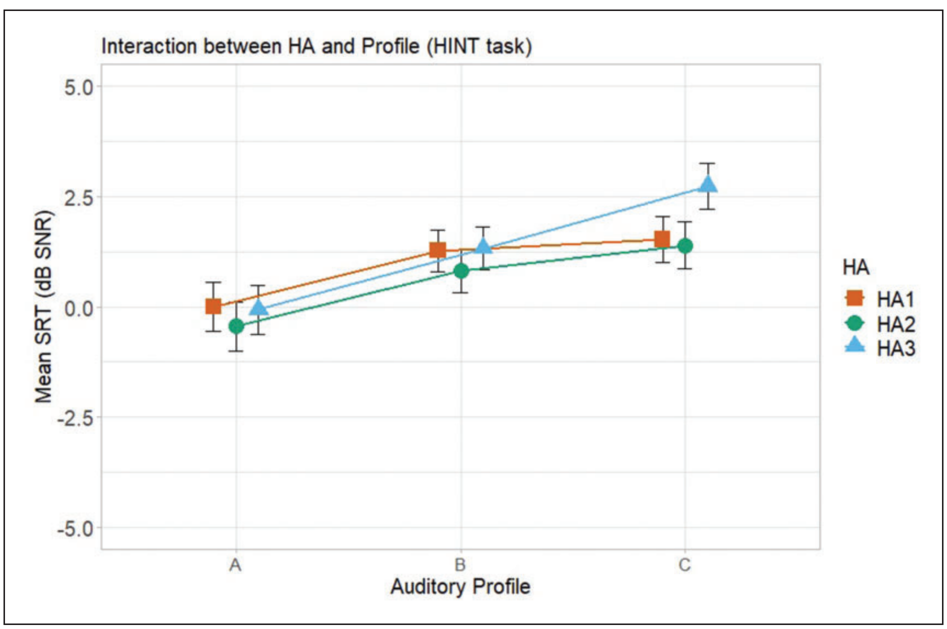

Figure 6. Mean SRTs of Profiles A, B, and C for Each of the Three Tested HAs. Error bars represent ±1 standard error of the mean. SRT = speech-reception threshold; SNR = signal-to-noise ratio; HINT = Hearing in Noise Test; HA = hearing aid.

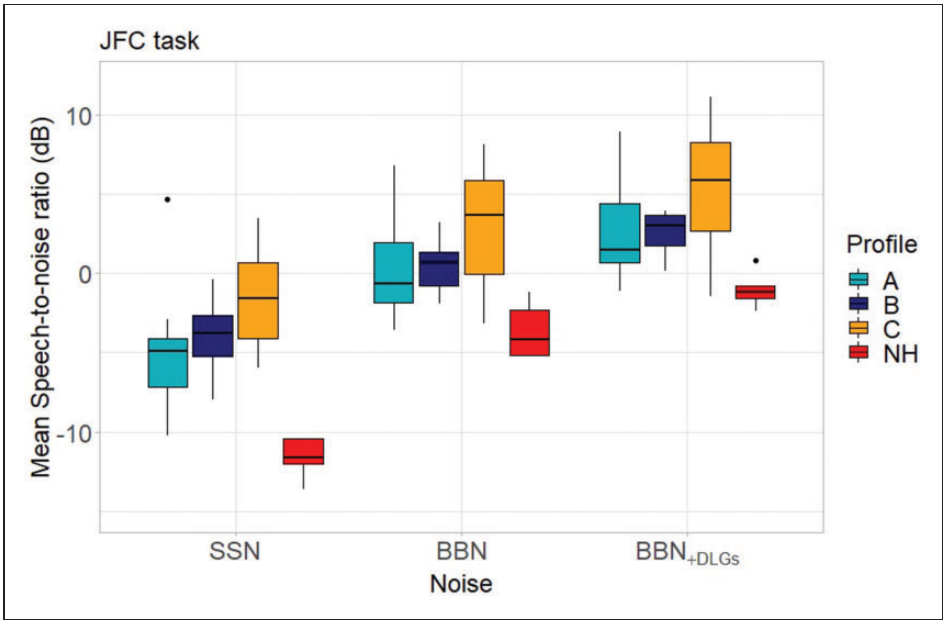

Figure 7. Boxplots of Mean Self-Adjusted Speech-to-Noise Ratios for the Three Auditory Profiles and NH Participants in the Three Noise Conditions. For the HA users, the data were averaged across the three HAs. SSN = speech-shaped noise; BBN = speech-shaped babble noise; BBN_{+DLGs} = BBN with intelligible dialogues; NH = normal-hearing; JFC = just follow conversation.

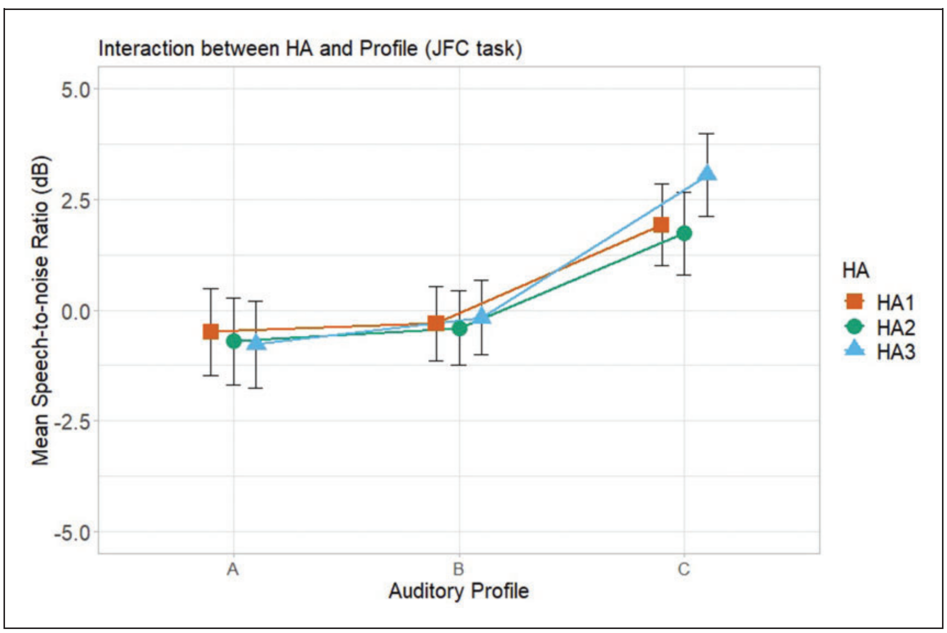

Figure 8. Mean Speech-to-Noise Ratios of Profile-A, Profile-B, and Profile-C HA Users for Each of the Tested HAs. Error bars represent ± 1 standard error of the mean. HA = hearing aid.

Correlation Analysis of HINT and JFC Results

Figure 9 shows a scatter plot of the HINT and JFC data from the HA users and NH participants averaged across the three noise conditions and HAs. According to Pearson's correlation coefficient, the two SIN outcomes were strongly correlated ($r = .73$, $p < .001$). The participants with the best SIN outcomes (i.e., the NH participants) are gathered in the bottom left-hand corner. The HA users who came closest to the NH participants belong mostly to Profile A, whereas the HA users who are furthest away are mainly from profiles C and B. In

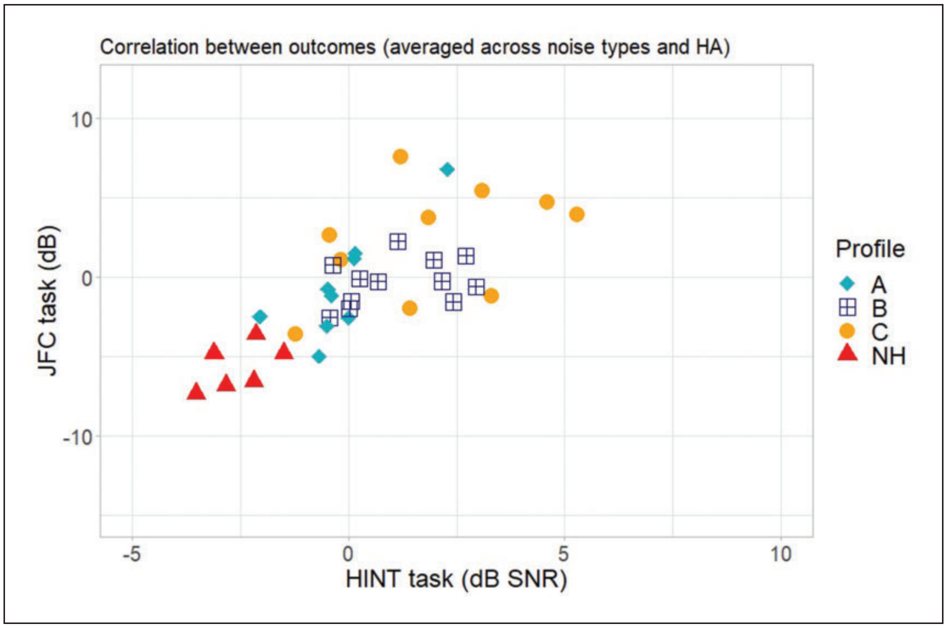

Figure 9. Scatter Plot of HINT Versus JFC Results Averaged Across the Three Noise Conditions and HAs. HA = hearing aid; NH = normal-hearing; JFC = just follow conversation; HINT = Danish Hearing in Noise Test; SNR = signal-to-noise ratio.

general, the spread in the data increased with increasing distance from the NH participants. This was due to some HA users showing a poor outcome on one but not the other task.

Discussion

This study used two SIN tasks (HINT and JFC) and three noise conditions (SSN, BBN, and BBN_{+DLGs}) to assess aided speech perception in 31 experienced HA users belonging to three different auditory profiles and six young NH participants. Each HA user was tested with three state-of-the-art HAs that had been fitted according to the recommended procedure of the respective manufacturer. The results showed an influence of the auditory profiles on the HINT task but not the JFC task. For the HINT task, there was also a main effect of HA, with the HA providing least overall gain resulting in the highest mean SRT. In general, the BBN_{+DLGs} noise condition resulted in the poorest outcomes, irrespective of speech task and auditory profile. Moreover, for both SIN outcomes, there was a significant interaction between auditory profile and HA, implying that Profile-C HA users were particularly disadvantaged when tested with HA3. In the following sections, these results are discussed.

Effects of Auditory Profile

Sanchez-Lopez et al. (2020) developed a method for classifying hearing-impaired listeners into four auditory profiles that can capture individual hearing deficits. In this study, this classification was expected to help explain differences in aided outcome. The Profile-A and Profile-C HA users performed differently on the HINT task. Given that profiles A and C differ substantially in the severity of their hearing deficits (Table 1), this finding was to be expected. As a matter of fact, it is in line with the results of a previous study, where speech recognition was assessed in the presence of cafeteria noise with simulated HA amplification (Wu et al., 2020). However, unlike previously, this study did not find a significant difference between Profile-A and Profile-B participants. A possible reason for this could be the selected noise conditions, which might have been unsuitable for eliciting differences in suprathreshold processing abilities among profiles A and B (see "Effects of Noise Type" section). Another reason could be the relatively small size of the Profile-A group ($N = 9$).

Whereas an effect of the auditory profiles was observed for the HINT task, this was not the case for the JFC task. An explanation for this could be that for some participants the two SIN outcomes were inconsistent. For example, for Profile A the variance was substantially larger in the JFC data than in the HINT data, while for Profile C it was comparable (Figures 5 and 7). In general, different HA outcome measures do not necessarily agree with each other (Larsby & Arlinger, 1994; Olsen et al., 2012; Valente et al., 2018). For instance, perceived HA sound quality or HA preference have been found to disagree with corresponding speech recognition scores (Brons et al., 2014; Neher, 2014). What is more, subjective assessments of HA-processed sound cannot be predicted from the degree of hearing loss (e.g., Arehart et al., 2015). Our results suggest that mismatches between the JFC and HINT outcomes occur particularly in Profile-A HA users. In our earlier study (Wu et al., 2020), Profile-A participants rated six simulated HA settings lower (worse) in terms of perceived noise annoyance than Profile-C participants, even though in terms of their speech recognition scores the two groups were similar. This discrepancy could indicate that Profile-A HA users are more critical in their assessments of HA-processed sound, possibly because their better suprathreshold hearing abilities allow them to detect finer stimulus differences (e.g., in terms of speech distortion). This could then explain why, in this study, the three profiles had comparable JFC results even though the Profile-A listeners achieved better HINT results compared with the Profile-B and profile-C listeners. Another explanation for the lack of an effect of the auditory profiles in the JFC data could be that the variance in these data was rather large. If more participants were tested, it is possible that differences between the profiles would emerge.

In principle, it is also possible that the profiles of some participants were not valid and that this could have affected the results. As evident from Figures 5 and 7, one Profile-A participant obtained much poorer results (BBN condition in HINT; SSN condition in JFC) than the other Profile-A participants, which could indicate that he was misclassified. However, as the HINT and JFC data of that participant were comparable across the three tested HAs, they were not excluded from the analyses. In any case, no other participant showed similarly divergent results, which suggests that the auditory profiles used in this study were valid.

Effects of Noise Condition

The noise type had a significant effect on both SIN outcomes. That is, the HINT and JFC results became poorer as the noise became more speech-like. The difference in mean scores between the HA users and NH controls was relatively constant for the HINT task but varied across noise conditions for the JFC task. The constant difference between the NH and HA-user groups on the HINT task is in line with the findings of Minnaar et al. (2011), who compared NH participants and HA users on a sentence-recognition task carried out in the presence of babble noise within six different room-acoustic settings. Regarding the JFC task, the group difference was larger in the SSN condition than in the two more speech-like noise conditions. In other words, the largest group difference between the NH listeners and HA users in terms of the JFC results occurred in the noise condition with the lowest (best) mean SRT. Larsby and Arlinger (1994) tested NH and unaided hearing-impaired listeners on a speech-recognition and a JFC task carried out in the presence of stationary noise and a single competing speech signal. They also found the largest group difference in terms of the JFC results for the noise condition with the lowest SRT, but in their case this was the single speech masker. It is currently unclear what the reasons for these findings are. Follow-up research is needed to study the influence of noise type on aided SIN outcome in different groups of listeners in more detail.

Previous research has observed relationships between specific suprathreshold hearing deficits and masking release (see “Introduction” section). For example, binaural and temporal processing deficits can be expected to result in reduced benefit from spatial separation of competing signals as well as fluctuations in noise level (Marrone et al., 2008; Moore, 2021). Given that the auditory profiles reflect the listeners’ suprathreshold hearing abilities (Table 1), they should in principle also be sensitive to different speech outcomes in the tested noise scenarios. The SSN and BBN signals used in this study differed in terms of their amplitude modulation characteristics. Despite this, the SRTs of the NH participants did not differ across the SSN and BBN conditions ($p = .97$), while for the HA users, the SRTs were poorer in the BBN condition compared with the SSN condition ($p < .001$). This would seem to suggest that the amplitude modulations in the BBN signal were too small to facilitate temporal masking release for the NH listeners. This could then also explain why no difference between Profile-A and Profile-B listeners (better vs. poorer temporal processing abilities; see Table 1) emerged. Furthermore, the three tested noise conditions did not differ in terms of their spatial properties. As a consequence, and in contrast to other studies that found HA users to vary substantially in their benefit from spatial separation of competing signals (Neher et al., 2009; Nuesse et al., 2018), this study was unable to evoke differences in binaural processing. Finally, in the BBN_{+DLGs} condition, which included intelligible speech maskers, HA users with severe suprathreshold hearing deficits (Profile C) were expected to have much poorer outcomes, especially compared with HA users with mild deficits (Profile A). However, the results showed that the difference between the profiles in the BBN_{+DLGs} condition did not differ from other noise conditions. This suggests that all HA-user groups encountered similar levels of difficulty when the noise changed from unintelligible to intelligible. In follow-up research, it would be interesting to include noise conditions differing clearly in terms of their spatial and temporal properties to investigate how this affects the auditory profiles.

Effects of HA

There was an effect of HA on HINT outcome, which was independent of auditory profile and noise condition. This was because the HA3 scores were poorer than the HA1 and HA2 scores. An interaction between auditory profile and HA was found for both the HINT and the JFC outcomes (Figures 6 and 8). That is, the Profile-C HA users obtained significantly poorer HINT and JFC results when tested with HA3. It seems likely that this was due to the Profile-C participants having the largest audiometric hearing losses (Figure 1) and HA3 providing least gain overall (Figure 4). Given that HA2 and HA3 provided similar amounts of gain at 2000 Hz and above, the lower gain in the 500- to 1000-Hz range seems to explain the poor outcomes of the Profile-C participants.

It has been suggested that generic gain prescription rules, like NAL-NL2, together with real-ear verification are advantageous compared with the proprietary fitting procedures developed by the HA manufacturers, partly because the former tend to provide higher gains and thus better speech audibility (Abrams et al., 2012; Jindal et al., 2018; Sanders et al., 2015). This study, however, indicates that HA users do not always benefit from more gain as far as SIN outcome is concerned. For example, HA1 for the Profile-B participants provided least gain, but the SIN outcomes with these fittings did not differ from the other two HAs (Figure 4). On the other hand, the SIN results obtained with HA1 and HA2 did not differ from each other, even though HA2 provided more gain at 500 and 1000 Hz than HA1. In general, HA2 provided more gain at these frequencies compared with the other two HAs and the NAL-NL2 targets. Future studies should check whether additional gain in this frequency range is also beneficial for other important HA outcomes (e.g., listening comfort). Furthermore, NAL-NL2 target gains are known to be higher in the high-frequency (>4 kHz) range. In future studies, it would be interesting to investigate the consequences of this in relation to the auditory profiles.

In clinical practice, the choice of HA *brand* typically does not involve considerations of the patient's hearing deficits. As the fitting rationales of different manufacturers can prescribe different gains for the same audiogram (Keidser et al., 2003), this may have important consequences for treatment outcome, as suggested by this study. Particularly, Profile-C listeners would seem to be candidates for a more structured fitting strategy. The HAs currently fitted in the clinics are able to provide amplification and thus improve audibility, but they are limited in their ability to compensate for suprathreshold hearing deficits (Lesica, 2018). Although modern HAs come with advanced features such as noise reduction or directional processing, their efficacy with respect to improving SIN outcome is mixed (e.g., Brons et al., 2014; Lunner & Sundewall-Thorén, 2007; Neher, 2014; Neher & Wagener, 2016). Presumably, this is related to the fact that the diversity of individual hearing impairments is neglected in their design. More personalized HA rehabilitation can be expected to benefit from a deeper understanding of the perceptual consequences caused by various types of hearing deficits and the incorporation of this knowledge in the HA processing. In this context, the auditory profiles tested here can potentially serve as a useful basis for more individualized HA treatment (Sanchez-Lopez et al., 2021).

Conclusions

Using the auditory profiles from the BEAR project, it was possible to identify HA candidates with good and poor aided SIN outcomes. HA users with pronounced hearing deficits (in terms of both audiometric hearing loss and suprathreshold hearing deficits) were significantly affected by the choice of HA. These differences appeared to be related to differences in the gain prescribed by the proprietary fitting rationales. More generally speaking, proprietary (audiogram-based) HA fittings produced poorer SIN outcomes for individuals with pronounced hearing deficits compared with individuals with mild deficits. Overall, the auditory profiles can therefore provide a basis for follow-up investigations into the efficacy of new HA treatment methods aiming at more targeted solutions for specific hearing deficits.

Acknowledgments

The funding and collaboration of all partners is sincerely acknowledged. The authors thank Søren Laugesen (Interacoustics Research Unit, Denmark) for input with respect to the generation of the noise signals and Nicoline Gotholt Madsen, Kathrine Jørgensen, Louise Thygesen Smidt, Sagal Rådberg Nagbøl, and Stine Christiansen (University of Southern Denmark) for help with the data collection.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by Innovation Fund Denmark Grand Solutions 5164-00011B (BEAR project) as well as GN Hearing, Oticon, and WS Audiology.

ORCID iDs

Mengfan Wu https://orcid.org/0000-0001-8794-4490
Tobias Neher https://orcid.org/0000-0002-1107-9274

References

Abrams, H. B., Chisolm, T. H., McManus, M., & McArdle, R. (2012). Initial-fit approach versus verified prescription: Comparing self-perceived hearing aid benefit. *Journal of the American Academy of Audiology*, *23*(10), 768–778. https://doi.org/10.3766/jaaa.23.10.3

Abrams, H. B., & Kihm, J. (2015). An introduction to MarkeTrak IX: A new baseline for the hearing aid market. *Hearing Review*, *22*(6), 16.

Anderson, M., Arehart, K. H., & Souza, P. E. (2018). Survey of current practice in the fitting and fine-tuning of common signal-processing features in hearing aids for adults. *Journal of the American Academy of Audiology*, *29*(2), 118–124. https://doi.org/10.3766/jaaa.16107

Arbogast, T. L., Mason, C. R., & Kidd, G., Jr. (2005). The effect of spatial separation on informational masking of speech in normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America*, *117*(4), 2169–2180. https://doi.org/10.1121/1.1861598

Arehart, K., Souza, P., Kates, J., Lunner, T., & Pedersen, M. S. (2015). Relationship between signal fidelity, hearing loss and working memory for digital noise suppression. *Ear and Hearing*, *36*(5), 505. https://doi.org/10.1097/AUD.0000000000000173

Bacon, S. P., Opie, J. M., & Montoya, D. Y. (1998). The effects of hearing loss and noise masking on the masking release for speech in temporally complex backgrounds. *Journal of Speech, Language, and Hearing Research, 41*(3), 549–563. doi:10.1044/jslhr.4103.549

Baker, R., & Hazan, V. (2011). DiapixUK: Task materials for the elicitation of multiple spontaneous speech dialogs. *Behavior Research Methods*, *43*(3), 761–770. DOI: 10.3758/s13428-011-0075-y

Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. doi: 10.18637/jss.v067.i01

Bernstein, J. G. W., Danielsson, H., Hällgren, M., Stenfelt, S., Rönnberg, J., & Lunner, T. (2016). Spectrotemporal modulation sensitivity as a predictor of speech-reception performance in noise with hearing aids. *Trends in Hearing*, *20*, 2331216516670387. https://doi.org/10.1177/2331216516670387

Bisgaard, N., Vlaming, M. S., & Dahlquist, M. (2010). Standard audiograms for the IEC 60118-15 measurement procedure. *Trends in Amplification*, *14*(2), 113–120. https://doi.org/10.1177/1084713810379609

Brand, T., & Hohmann, V. (2002). An adaptive procedure for categorical loudness scaling. *The Journal of the Acoustical Society of America*, *112*(4), 1597–1604. https://doi.org/10.1121/1.1502902

Brons, I., Houben, R., & Dreschler, W. A. (2014). Effects of noise reduction on speech intelligibility, perceived listening effort, and personal preference in hearing-impaired listeners. *Trends in Hearing*, *18*. https://doi.org/10.1177/2331216514553924

Brungart, D. S. (2001). Informational and energetic masking effects in the perception of two simultaneous talkers. *The Journal of the Acoustical Society of America*, *109*(3), 1101–1109. https://doi.org/ 10.1121/1.1345696

Eddins, D. A., Arnold, M., Klein, A., & Ellison, J. (2013). Individual variability in unaided and aided measurement of the acceptable noise level. *Seminars in Hearing*, *34*(02), 118–127. https://doi.org/10.1055/s-0033-1341348

Füllgrabe, C., Harland, A. J., Sęk, A. P., & Moore, B. C. (2017). Development of a method for determining binaural sensitivity to temporal fine structure. *International Journal of Audiology*, *56*(12), 926–935. https://doi.org/10.1080/14992027.2017.1366078

Füllgrabe, C., Moore, B. C., & Stone, M. A. (2015). Age-group differences in speech identification despite matched audiometrically normal hearing: Contributions from auditory temporal processing and cognition. *Frontiers in Aging Neuroscience*, *6*, 347. https://doi.org/10.3389/fnagi.2014.00347

George, E. L., Festen, J. M., & Houtgast, T. (2006). Factors affecting masking release for speech in modulated noise for normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical society of America, 120*(4), 2295–2311. doi:10.1121/1.2266530

Holube, I., Fredelake, S., Vlaming, M., & Kollmeier, B. (2010). Development and analysis of an International Speech Test Signal (ISTS). *International Journal of Audiology*, *49*(12), 891–903. https://doi.org/10.3109/14992027.2010.506889

Hornsby, B. W., Ricketts, T. A., & Johnson, E. E. (2006). The effects of speech and speechlike maskers on unaided and aided speech recognition in persons with hearing loss. *Journal of the American Academy of Audiology*, *17*, 432–447. https://doi.org/10.3766/jaaa.17.6.5

Humes, L. E. (2016). Understanding the speech-understanding problems of older adults. *Journal of the Acoustical Society of America*, *139*(4), 2042–2042. https://doi.org/10.1121/1.4950038

Jindal, J., Hawkins, A.-M., & Murray, M. (2018). Guidance on the verification of hearing devices using probe microphone measurements. In *Practice guidance*. British Society of Audiology.

Johannesen, P. T., Pérez-González, P., Kalluri, S., Blanco, J. L., & Lopez-Poveda, E. A. (2016). The influence of cochlear mechanical dysfunction, temporal processing deficits, and age on the intelligibility of audible speech in noise for hearing-impaired listeners. *Trends in Hearing*, *20*. https://doi.org/10.1177/2331216516641055

Keidser, G., Brew, C., & Peck, A. (2003). Proprietary fitting algorithms compared with one another and with generic formulas. *The Hearing Journal*, *56*(3), 28–32.

Keidser, G., Dillon, H., Flax, M., Ching, T., & Brewer, S. (2011). The NAL-NL2 prescription procedure. *Audiology Research*, *1*(1), 88–90. https://doi.org/10.4081/audiores.2011.e24

Kidd, G., Jr., Mason, C. R., Best, V., Roverud, E., Swaminathan, J., Jennings, T., ... Steven Colburn, H. (2019). Determining the energetic and informational components of speech-on-speech masking in listeners with sensorineural hearing loss. *The Journal of the Acoustical society of America*, *145*(1), 440–457. https://doi.org/10.1121/1.5087555

Kidd, G., Mason, C. R., Richards, V. M., Gallun, F. J., & Durlach, N. I. (2008). Informational masking. In W. A.

Yost, A. N. Popper, & R. R. Fay (Eds.), *Auditory perception of sound sources* (pp. 143–189). Springer.

Larsby, B., & Arlinger, S. (1994). Speech recognition and just-follow-conversation tasks for normal-hearing and hearing-impaired listeners with different maskers. *Audiology*, *33*(3), 165–176. https://doi.org/10.3109/00206099409071877

Lesica, N. A. (2018). Why do hearing aids fail to restore normal auditory perception? *Trends in Neurosciences*, *41*(4), 174–185. https://doi.org/10.1016/j.tins.2018.01.008

Lőcsei, G., Pedersen, J. H., Laugesen, S., Santurette, S., Dau, T., & MacDonald, E. N. (2016). Temporal fine-structure coding and lateralized speech perception in normal-hearing and hearing-impaired listeners. *Trends in Hearing*, *20*. https://doi.org/10.1177/2331216516660962

Lopez-Poveda, E. A., Johannesen, P. T., Perez-González, P., Blanco, J. L., Kalluri, S., & Edwards, B. (2017). Predictors of hearing-aid outcomes. *Trends in Hearing*, *21*. https://doi.org/10.1177/2331216517730526

Lunner, T., & Sundewall-Thorén, E. (2007). Interactions between cognition, compression, and listening conditions: Effects on speech-in-noise performance in a two-channel hearing aid. *Journal of the American Academy of Audiology*, *18*(7), 604–617. https://doi.org/10.3766/jaaa.18.7.7

Marrone, N., Mason, C. R., & Kidd Jr, G. (2008). Evaluating the benefit of hearing aids in solving the cocktail party problem. *Trends in Amplification*, *12*(4), 300–315. https://doi.org/10.1177/1084713808325880

Mattys, S. L., Davis, M. H., Bradlow, A. R., & Scott, S. K. (2012). Speech recognition in adverse conditions: A review. *Language and Cognitive Processes*, *27*(7–8), 953–978. https://doi.org/10.1080/01690965.2012.705006

Mendel, L. L. (2007). Objective and subjective hearing aid assessment outcomes. *American Journal of Audiology*. Advance online publication. https://doi.org/10.1044/1059-0889(2007/016)

Minnaar, P., Breitsprecher, C., & Holmberg, M. (2011). Simulating complex listening environments in the laboratory for testing hearing aids. Proceedings of Forum Acusticum, Aalbog, Denmark.

Moore, B. C. J. (2021). Effects of hearing loss and age on the binaural processing of temporal envelope and temporal fine structure information. *Hearing research, 402*, 107991–107991. https://doi.org/10.1016/j.heares.2020.107991

Neher, T. (2014). Relating hearing loss and executive functions to hearing aid users' preference for, and speech recognition with, different combinations of binaural noise reduction and microphone directionality. *Frontiers in Neuroscience*, *8*, 391. https://doi.org/10.3389/fnins.2014.00391

Neher, T., Behrens, T., Carlile, S., Jin, C., Kragelund, L., Petersen, A. S., & Schaik, A. V. (2009). Benefit from spatial separation of multiple talkers in bilateral hearing-aid users: Effects of hearing loss, age, and cognition. *International Journal of Audiology*, *48*(11), 758–774.

Neher, T., & Wagener, K. C. (2016). Investigating differences in preferred noise reduction strength among hearing aid users. *Trends in Hearing*, *20*, 2331216516655794. https://doi.org/10.1177/2331216516655794

Nielsen, J. B., & Dau, T. (2011). The Danish Hearing in Noise Test. *International Journal of Audiology*, *50*(3), 202–208. https://doi.org/10.3109/14992027.2010.524254

Nuesse, T., Steenken, R., Neher, T., & Holube, I. (2018). Exploring the link between cognitive abilities and speech recognition in the elderly under different listening conditions. *Frontiers in Psychology*, *9*, 678. https://doi.org/10.3389/fpsyg.2018.00678

Olsen, S. Ø., Lantz, J., Nielsen, L. H., & Brännström, K. J. (2012). Acceptable noise level (ANL) with Danish and non-semantic speech materials in adult hearing-aid users. *International Journal of Audiology*, *51*(9), 678–688. https://doi.org/10.3109/14992027.2012.692822

Plomp, R. (1978). Auditory handicap of hearing impairment and the limited benefit of hearing aids. *The Journal of the Acoustical society of America*, *63*(2), 533–549. https://doi.org/10.1121/1.2015802

Prosser, S., Turrini, M., & Arslan, E. (1991). Effects of different noises on speech discrimination by the elderly. *Acta Oto-Laryngologica, 111*(sup476), 136–142. https://doi.org/10.3109/00016489109127268

Rosen, S., Souza, P., Ekelund, C., & Majeed, A. A. (2013). Listening to speech in a background of other talkers: Effects of talker number and noise vocoding. *The Journal of the Acoustical Society of America*, *133*(4), 2431–2443. https://doi.org/10.1121/1.4794379

Sanchez-Lopez, R., Fereczkowski, M., Neher, T., Santurette, S., & Dau, T. (2020). Robust data-driven auditory profiling towards precision audiology. *Trends in Hearing*. Advance online publication. https://doi.org/10.1177/2331216520973539.

Sanchez-Lopez, R., Fereczkowski, M., Santurette, S., Dau, T., & Neher, T. (2021). Towards auditory profile-based hearing-aid fitting: Fitting rationale and pilot evaluation. *Audiology Research*, *11*(1), 10–21. https://doi.org/10.5281/zenodo.4421553

Sanchez-Lopez, R., Nielsen, S. G., Cañete, O., Fereczkowski, M., Wu, M., Neher, T., Dau, T., & Santurette, S. (2019). A clinical test battery for Better hEAring Rehabilitation (BEAR): Towards the prediction of individual auditory deficits and hearing-aid benefit. In M. Ochmann, M. Vorländer, & J. Fels (Eds.), *Proceedings of the 23rd International Congress on Acoustics* (pp. 3841–3848). Deutsche Gesellschaft für Akustik eV.

Sanders, J., Stoody, T., Weber, J., & Mueller, H. (2015). Manufacturers' NAL-NL2 fittings fail real-ear verification. *Hearing Review*, *21*(3), 24–32.

Santurette, S., & Dau, T. (2012). Relating binaural pitch perception to the individual listener's auditory profile. *The Journal of the Acoustical Society of America*, *131*(4), 2968–2986. https://doi.org/10.1121/1.3689554

Sørensen, A. J., Fereczkowski, M., & MacDonald, E. (2018). Task dialog by native-Danish talkers in Danish and English in both quiet and noise. http://doi.org/10.5281/zenodo.1204951

Valente, M., Oeding, K., Brockmeyer, A., Smith, S., & Kallogjeri, D. (2018). Differences in word and phoneme recognition in quiet, sentence recognition in noise, and subjective outcomes between manufacturer first-fit and hearing aids programmed to NAL-NL2 using real-ear measures. *Journal of the American Academy of Audiology*, *29*(08), 706–721. https://doi.org/10.3766/jaaa.17005

Wong, L. L., Ng, E. H., & Soli, S. D. (2012). Characterization of speech understanding in various types of noise. *The Journal of the Acoustical Society of America*, *132*(4), 2642–2651.

Woods, D. L., Arbogast, T., Doss, Z., Younus, M., Herron, T. J., & Yund, E. W. (2015). Aided and unaided speech perception by older hearing impaired listeners. *PLoS One*, *10*(3), e0114922. https://doi.org/10.1371/journal.pone.0114922

Wu, M., Sanchez-Lopez, R., El-Haj-Ali, M., Nielsen, S. G., Fereczkowski, M., Dau, T., Santurette, S., & Neher, T. (2020). Investigating the Effects of Four Auditory Profiles on Speech Recognition, Overall Quality, and Noise Annoyance With Simulated Hearing-Aid Processing Strategies. *Trends in Hearing, 24*. https://doi.org/10.1177/2331216520960861