# Perceptual evaluation of six hearing-aid processing strategies from the perspective of auditory profiling: Insights from the BEAR project

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The current study forms part of the Better hEAring Rehabilitation (BEAR) project, which aims at developing new clinical tools for characterizing individual hearing loss and for assessing hearing-aid (HA) benefit. Its purpose was to investigate potential interactions between four auditory profiles and three measures of HA outcome obtained for six HA processing strategies. Measurements were carried out in a realistic noise environment at signal-to-noise ratios that were set based on individual aided speech reception thresholds ($SRT_{50}$). Speech recognition scores and ratings of overall quality and noise annoyance were collected in two spatial conditions. The stimuli were generated with the help of a HA simulator and presented via headphones to 60 older, habitual HA users who had previously been profiled based on a data-driven approach (Sanchez-Lopez *et al.*, 2019). The four auditory profiles differed significantly in terms of mean aided $SRT_{50}$ and interacted significantly with the HA processing strategies for speech recognition in one spatial condition. Moreover, the correlation-pattern between the speech recognition scores and subjective ratings differed among the auditory profiles.

## INTRODUCTION

Hearing-aid (HA) benefit in noisy environments is known to vary substantially among users, and several researchers have investigated ways to improve individual HA outcome (e.g., Lopez-Poveda *et al.*, 2017). Additionally, modern HA technology offers various features to improve speech intelligibility, e.g., directional microphones (Keidser *et al.*, 2013), noise reduction (Brons *et al.*, 2014), and dynamic range compression (Picou *et al.*, 2015). Despite these efforts, clinical HA fittings are still mainly based on the audiogram, even though pure-tone hearing thresholds are unable to capture all the supra-threshold deficits induced by a hearing loss (Johannesen *et al.*, 2016; Plomp, 1978). Moreover, the advanced features are not utilized in a systematic way.

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The Better hEAring Rehabilitation (BEAR) project aims at developing new clinical tools for individual hearing loss characterization and HA benefit assessment. For that purpose, an auditory test battery and a data-driven approach for classifying listeners into four distinct auditory profiles were proposed in an earlier study (Sanchez-Lopez *et al.*, 2019). In that study, 75 participants from four auditory profiles differed in terms of their performance on various auditory measurements, as shown in Table 1. In the present study, 60 of the subjects tested by Sanchez-Lopez *et al.* (2019) participated and evaluated six processing strategies for HA treatment in three perceptual tasks.

The main purpose of the current study was to evaluate the perceptual HA outcomes of these six HA processing strategies in relation to the four auditory profiles. Furthermore, correlations between aided speech-in-noise intelligibility and the subjective ratings of overall quality and noise annoyance were analysed. Since a better speech recognition score with a given HA setting does not necessarily correspond to high preference for that HA setting (Cox *et al.*, 2016), we hypothesized that the four auditory profiles may help explain this inconsistency.

| Auditory Profile | Audibility | | Binaural processing | Loudness | Speech perception | Spectro-temporal |
|---|---|---|---|---|---|---|
| | LF | HF | | | | |
| **A** (n=14) | ☺ | 😐 | ☺ | ☺ | ☺ | ☺ |
| **B** (n=13) | ☺ | ☹ | 😐 | 😐 | ☹ | ☹ |
| **C** (n=20) | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ |
| **D** (n=8) | ☹ | 😐 | ☺ | ☹ | ☺ | 😐 |

**Table 1:** Overall relative performance on the main measures from the BEAR auditory test battery. LF = low frequencies, HF = high frequencies. ☺: better performance, ☹: poorer performance, and 😐: average performance.

## METHODS

The perceptual evaluation was carried out in a simulated speech-in-noise environment and consisted of a speech recognition task and a subjective rating task. To achieve high face validity, testing conditions were chosen to reflect the difficulties that older HA users often encounter in complex noisy scenarios (Neher *et al.*, 2011; Prosser *et al.*, 1991).

### Participants

Sixty subjects aged 60-80 years (mean = 70.8 years) were recruited for the study. Twenty-nine of them were tested at Odense University Hospital, Odense, while the other ones were tested at Bispebjerg Hospital, Copenhagen. All participants had bilateral symmetrical sensorineural hearing loss and were experienced HA users. The range of hearing loss configurations was chosen to lie in-between the N1 and N4 standard audiograms (Bisgaard *et al.*, 2010).

Prior to this study, all participants completed a comprehensive auditory test battery developed by Sanchez-Lopez *et al*. (2020). Based on these measurements, the participants were classified into one of four auditory profiles using a data-driven approach (Sanchez-Lopez *et al.*, 2019). Five of the participants tested here could not be reliably allocated to any of these profiles and were thus not included in the data analysis described here. The distribution of the remaining 55 participants was as shown in the first column of Table 1.

**Test setup**

The measurements were performed either in an anechoic chamber or a soundproof booth. Audio playback was via an RME Fireface UC soundcard, an SPL Phonitor Mini amplifier and a pair of Sennheiser HDA200 headphones. All stimuli were generated with the help of a hearing-aid simulator (HASIM) implemented in Matlab (Sanchez-Lopez *et al.*, 2018).

**Stimuli**

The target speech stimuli were DANTALE-II sentences spoken by a female native Danish speaker (Wagener *et al.*, 2003). The target speech was presented from either 0º (front) or 90º (the side of the 'better' ear according to previously conducted unaided speech-in-noise measurements). The background noise was a spatially diffuse cafeteria noise recorded in a university canteen with a pair of HA satellites. In addition, the International Speech Test Signal (Holube *et al.*, 2010) was used as a directional distractor from either 90º (target speech from 0º) or 0º (target speech from 90º). The directional distractor was presented at a signal-to-noise ratio (SNR) of +2 dB relative to the diffuse cafeteria noise.

**Hearing-aid simulator (HASIM)**

The HASIM included directional processing (omnidirectional, fixed cardioid or fixed binaural beamformer setting), noise reduction (maximal attenuation of 0, 5 or 15 dB) and amplitude compression (attack times of 5 or 250 ms and release times of 10 or 1250 ms for 'fast' and 'slow', respectively). For each listener, gains were set according to the NAL-NL2 fitting rule (Keidser *et al.*, 2011). Four HA processing strategies (Table 2) were selected to maximize differences in the sound processing. HA1 corresponded to very basic processing and served as a reference. HA6 resembled typical 'commercial' HA processing. For further details about the HASIM, see Sanchez-Lopez *et al.* (2018).

| | Directional processing | Noise reduction | Amplitude compression |
|---|---|---|---|
| HA1 | Omnidirectional | Off | Slow |
| HA2 | Omnidirectional | Strong | Fast |
| HA3 | Binaural beamformer | Off | Slow |
| HA4 | Binaural beamformer | Strong | Slow |
| HA5 | Binaural beamformer | Strong | Fast |
| HA6 | Cardioid | Mild | Slow |

**Table 2:** Description of the six tested HA processing strategies

### Procedure

Each participant completed two visits. At the first visit, aided speech reception thresholds ($SRT_{50}$) were measured in an adaptive procedure (1-down 1-up procedure with a step size of 4 dB for the first five trials and 2 dB afterwards) to establish a baseline performance level for each participant. For the aided $SRT_{50}$ measurements, the baselines of the stimuli were amplified according to individual gains (NAL-NL2 prescription for an input level of 65 dB SPL) and the target was amplified linearly during measurements. Aided $SRT_{50}$ was only tested in the 0° condition. The six HA processing strategies were then evaluated for both spatial conditions using a speech recognition task at a fixed SNR that corresponded to the individual aided $SRT_{50}$. The speech recognition measurements were repeated at the second visit.

The subjective assessment included ratings of overall quality and noise annoyance for the six HA in two spatial conditions. A multi-stimulus comparison method with a hidden anchor ('MUSHA') was implemented in the SenseLabOnline 4.0.2 software (SenseLab, 2017). The anchor stimulus used for the subjective ratings was a speech-in-noise stimulus that had been heavily distorted using random binary mask processing to approximate undesired spectral distortion of the tested noise reduction scheme. On a given trial, participants were presented with a graphical user interface containing seven playback buttons and sliders (6 HA settings + 1 anchor stimulus). Each stimulus was rated four times per spatial condition. The test SNR used for the subjective ratings corresponded to $SRT_{50}$ + 4 dB.

## RESULTS

### Effect of auditory profile on $SRT_{50}$

On average, profile A had the lowest $SRT_{50}$ (mean = –0.5 dB SNR, SD = 1.2 dB SNR) while profile C had the highest (mean = 5.1 dB SNR, SD = 3.6 dB SNR). According to a series of independent *t*-tests, profile B (mean = 2.7 dB SNR, SD = 2.3 dB SNR) and profile C differed significantly from profile A and profile D (mean = 0.6 dB SNR, SD = 1.2 dB SNR), respectively (all $p < 0.01$).

### Effects of auditory profile on HA outcomes

For both speech recognition (Figure 1) and the subjective ratings, listeners from the four auditory profiles showed similar patterns of benefit from the six HA processing strategies. More specifically, all auditory profiles gained larger benefits from the same or similar HA processing strategies for each outcome measure.

To assess the effect of auditory profile on the different HA outcomes, linear mixed effects models were implemented. The dependent variable was the individual standardized score. For speech recognition, due to the data being split based on spatial condition, the model included four components (HA, auditory profile (AP), HA*test SNR, HA*AP). The random effect was the individual intercept. For the subjective ratings, the model included nine parts (HA, spatial condition (spa), AP, HA*spa, HA*AP, AP*spa, HA*test SNR, spa*test SNR, HA*spa*AP).

For all three outcomes, a significant effect of HA was found (all $p < 0.001$). For the subjective ratings, the effects of spa and HA*spa were also significant (all $p < 0.001$). Furthermore, for speech recognition assessed in the 90º spatial condition there was a significant interaction between AP and HA ($F_{9, 201} = 4.3$, $p < 0.001$), which was driven by low-benefit HA strategies (HA2 and HA3, see Fig. 1). Overall, there were no significant main effects of auditory profile or significant interaction with auditory profile (all $p > 0.05$).

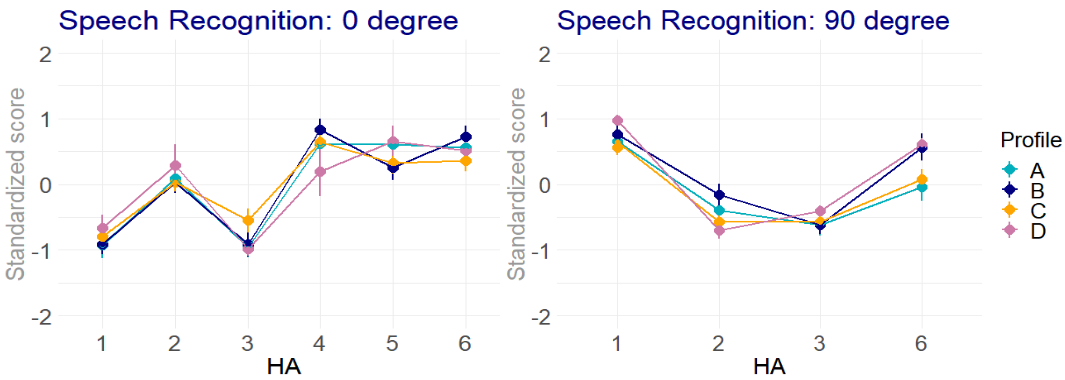


**Fig. 1:** Mean standardized speech recognition scores and standard errors for each test condition and auditory profile. Scores were averaged across test and retest. HA4 and HA5 were excluded in the 90º condition because of strong flooring effects.

### Correlation analysis

Spearman's correlation coefficients were calculated to investigate potential relations between the three outcome measures across the four auditory profiles (Table 3). In general, more correlations were found for the 90º spatial condition than for the 0º spatial condition. In particular, the overall quality ratings were positively correlated with the speech scores for all auditory profiles in the 90º (but not the 0º) condition. Some differences among the four profiles were observed. Participants from profiles B showed relatively large, positive correlations between sentence recognition scores and both types of subjective ratings, while for profile A, which had a near-normal $SRT_{50}$, the different outcomes were not significantly correlated in most cases.

| | | OVERALL & SPEECH | | NOISE & SPEECH | |
|---|---|---|---|---|---|
| Profile | | 0° | 90° | 0° | 90° |
| A | *r* | 0.07 | **0.40** | 0.02 | 0.17 |
| | *p* | 0.52 | <0.01 | 0.88 | 0.22 |
| B | *r* | **0.29** | **0.60** | **0.34** | **0.29** |
| | *p* | 0.02 | <0.001 | <0.01 | 0.04 |
| C | *r* | -0.01 | **0.61** | **0.36** | **0.25** |
| | *p* | 0.96 | <0.001 | <0.001 | 0.04 |
| D | *r* | 0.08 | **0.71** | 0.04 | **0.57** |
| | *p* | 0.60 | <0.001 | 0.81 | <0.01 |

**Table 3.** Results of correlation analyses performed on the speech scores and subjective ratings for each auditory profile. OVERALL = overall quality, SPEECH = speech recognition, NOISE = noise annoyance.

## DISCUSSION

In the current study, speech recognition measurements and subjective ratings were applied to investigate potential links between four auditory profiles and response to six different HA processing strategies in a simulated speech-in-noise environment. Differences in aided $SRT_{50}$ between four auditory profiles indicate different needs in terms of SNR improvement in HA processing. However, the four profiles barely differed in terms of their responses to the six tested HA processing strategies. One possible explanation could be that the participants were equated in terms of baseline performance level, which was based on their aided $SRT_{50}$. In other words, both the HASIM and the participants were exposed to different input signals.

Another potential explanation for the lack of differences among the four profiles could be that the acoustic scene contained only one type of noise. It is possible that the use of a multi-talker scenario or more fluctuating noises would elicit more pronounced differences among the profiles in terms of their ability to utilize spatial and temporal cues in such scenarios.

Moreover, in the present study, a limited set of HA settings were considered, with gains being prescribed according to the NAL-NL2 rule in all conditions. Previous research suggested that individuals with sloping audiograms obtain larger benefits from different HA amplification than individuals with flat audiograms (Keidser and Grant, 2001). Thus, it is possible that individuals from four auditory profiles obtain high HA benefit from different amplification rationales. Whether there is a three-way interaction between HA setting, amplification rationale and auditory profile in terms of perceptual HA outcome requires further study in the future.

The correlation analyses revealed that the four auditory profiles differed in terms of the extent to which speech recognition is related to overall quality and noise annoyance. For profile B, there were consistent positive correlations between the two types of measurements. This result might indicate that for profile B listeners HA preference is governed by the clarity or naturalness of the target speech. However, for profiles A and D, this was only the case in the 90° condition. Considering that these two groups were tested at lower SNRs, it is reasonable to think that the HA processing strategies rendered the speech more unclear or distorted in this condition.

It is well established that HA benefit in complex speech-in-noise environments depends on both auditory and non-auditory factors (Gatehouse *et al.*, 2006). Our study suggests that preference for HA processing can be broken down into different types of psychoacoustic function. Whether those auditory factors are indeed linked to a general preference for speech naturalness requires further research. More generally, the question of whether the auditory profiles tested here influence HA outcome still needs further investigation. Ideally, this work should use real HAs, various background noises and aided outcome measures, and should also provide the participants with the possibility to acclimatize to the tested HA settings.

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