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# Auditory profiling and hearing-aid satisfaction in hearing-aid candidates

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## ABSTRACT

**INTRODUCTION:** Hearing-impaired (HI) listeners often complain about difficulties communicating in the presence of background noise, although audibility may be restored by a hearing-aid (HA). The audiogram typically forms the basis for HA fitting, i.e. people with similar audiograms are given the same prescription by default. This study aimed at identifying clinically relevant tests that may serve as an informative addition to the audiogram and which may relate more directly to HA satisfaction than the audiogram does.

**METHODS:** A total of 29 HI and 26 normal-hearing listeners performed tests of spectral and temporal resolution, binaural hearing, speech intelligibility in stationary and fluctuating noise and a working-memory test. Six weeks after HA fitting, the HI listeners answered a questionnaire evaluating HA treatment.

**RESULTS:** No other measures than masking release between fluctuating and stationary noise correlated significantly with audibility. The HI listeners who obtained the least advantage from fluctuations in background noise in terms of speech intelligibility experienced greater HA satisfaction.

**CONCLUSION:** HI listeners have difficulties in different hearing domains that are not predictable from their audiogram. Measures of temporal resolution or speech perception in both stationary and fluctuating noise could be relevant measures to consider in an extended auditory profile.

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**TRIAL REGISTRATION:** The protocol was approved by the Science Ethics Committee of the Capital Region of Denmark (reference H-3-2013-004).

It has been estimated that 30% of Danish hearing-aid (HA) users found that listening situations improved only moderately, slightly or not at all after HA prescription [1], suggesting inadequate HA treatment. Pure-tone audiometry typically forms the basis for providing and fitting HA devices. Patients with the same audiometric profile may therefore experience differences in HA satisfaction.

Although audibility may be restored by a HA, users often complain about communicating in the presence of background noise. The audiogram has been found to correlate well with speech intelligibility in quiet, but to correlate poorly in noisy contexts [2, 3]. Moreover, hear-

ing-impaired (HI) listeners with normal or near-normal low-frequency pure-tone hearing thresholds may show speech identification deficits when the speech spectrum is limited to regions of normal or near-normal hearing [4]. Speech intelligibility in noise has also been found to correlate with temporal fine-structure (TFS) processing abilities reflected by, e.g., frequency discrimination [2, 5]; and TFS processing deficits can be present despite near-normal thresholds [6]. The evaluation of a test battery including different hearing domains has also shown that HI listeners can suffer from auditory deficits that do not necessarily correlate with the audiogram [7].

Despite compelling evidence that the audiogram alone does not sufficiently characterise hearing loss, it remains unclear which additional properties of hearing function should be assessed in the clinic to provide adequate HA rehabilitation. The aim of the present study was to evaluate whether a clinical auditory profile including different psychoacoustic and cognitive tests adds relevant information to the audiogram. The auditory domains of interest were spectral and temporal resolution, TFS processing and speech perception in noise. Another aim was to evaluate HA satisfaction in relation to the auditory profile to investigate if specific test outcomes relate to HA satisfaction.

## METHODS

### Listeners

A total of 29 HI listeners (aged 52-80 years, mean age 68.4 years, 13 females, eight new and 21 experienced HA users) and 26 listeners with near-normal hearing thresholds (NHT listeners; aged 41-70 years, mean age 55.8 years, 18 females) participated. The term “near-normal” reflects the fact that thresholds were elevated in some listeners at high frequencies. The NHT group was included to obtain profile outcomes for a population in a similar age range but without hearing-sensitivity difficulties, and to observe the extent of individual differences within this group. **Figure 1** shows mean audiograms for the two groups.

### Experimental set-up

All measurements were conducted via a PC in a sound-proof booth. The stimuli were generated in MATLAB and presented via a Fireface UCX sound card. For audiomet-

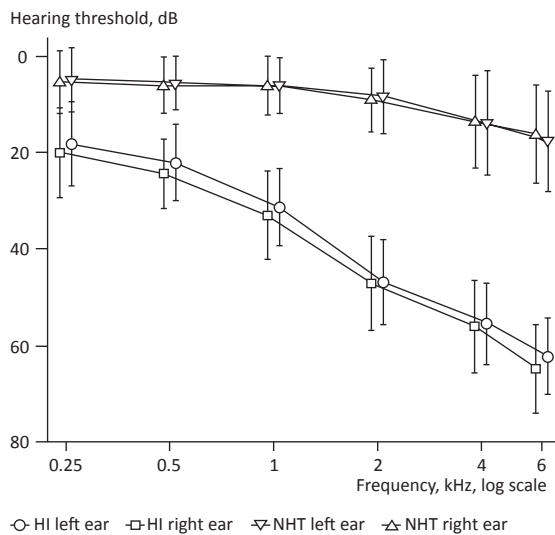
## ORIGINAL ARTICLE

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**FIGURE 1**

Characterisation of participants. Mean pure-tone hearing-thresholds for all hearing-impaired (HI) and near-normal hearing thresholds (NHT) listeners. Error bars show the standard deviation for the respective frequency. HI listeners: The inclusion criteria were sensorineural high-frequency hearing loss, bilateral hearing-aid therapy, age of 18-80 years, and Danish native language; the exclusion criteria were threshold asymmetry > 15 dB hearing level, asymmetry in speech discrimination > 20%, or conductive hearing loss. NHT listeners: The inclusion criteria were pure-tone average < 20 dB hearing level at 0.5, 1, and 1.5 kHz; pure-tone average < 30 dB hearing level at 2, 3, and 4 kHz, age of 18-80 years, and Danish native language; the exclusion criteria were threshold asymmetry > 15 dB hearing level or asymmetry in speech discrimination > 20%.



ric measurements, Interacoustics AC40 and AC440 connected to TDH39 headphones or Madsen Orbiter OB922 connected to HDA200 headphones were used. Insert earphones (EAR 3A) were used in listeners with a small auditory canal.

### General procedure

For pre-examination, air and bone conduction pure-tone thresholds from 250-8,000 Hz were measured. The test battery was always scheduled for another day than the day of the pre-examination and HA fitting. For NHT listeners, the pre-examination and the test battery were conducted in one session. A standardised written and verbal introduction was given prior to each test. All tests contained a training run. The cognitive test was carried out before the psychoacoustic measurements, the sequence of which was randomised. All auditory tests were conducted without HA.

### The test battery

A summary of the tests conducted and the corresponding outcome measures is given in **Table 1**. A brief description of all tests is provided below.

### Reading span

The test was used to evaluate working memory storage and processing [8]. The main task was to recall the first or the final word in a sequence of sentences presented visually on a screen. The remembered words were pronounced out loud. The experimenter registered the answers. The secondary task was to assess continuously if each sentence was correct or absurd. A total of 54 sentences (27 correct and 27 absurd) were presented.

### Combined spectral and temporal resolution

Auditory spectral and temporal resolutions were tested using a modified version of the combined spectral and temporal resolution (F&T) test [9]. The task was to detect a pulsed 275-ms tone at 500 Hz in the presence of broadband threshold-equalising noise containing no gap, a three-equivalent rectangular bandwidths wide spectral gap around the centre frequency or a 50-ms temporal gap. A test frequency of 500 Hz was chosen to minimise the effect of elevated hearing thresholds on the results, which are more likely at higher test frequencies [7]. The noise level was fixed at 55 dB sound pressure level (SPL). The tone level was varied adaptively using a Békésy tracking method with a starting value of 70 dB SPL. Each condition was measured twice, monaurally in both ears. The sequence of noise conditions and ears was randomised.

### Interaural-phase-difference detection

Binaural TFS processing was evaluated by measuring the upper frequency limit for which an interaural-phase-difference (IPD) of 180° was detectable [10]. Good abilities in binaural TFS processing are important for, e.g., sound localisation. The task was to detect which of three stimulus intervals contained an IPD and thus sounded more spacious than the other two intervals with no IPD. The stimulus was a sinusoidal-amplitude-modulated pure-tone with a 40-Hz modulation rate and a modulation depth of 1. The presentation level was 35 dB sensation level relative to pure-tone hearing-thresholds in each ear. The start frequency was 250 Hz and was changed according to a two-up one-down rule in step-sizes of a half, a fifth, and a tenth octave that decreased after each lower reversal. Two thresholds were obtained per listener.

### Hearing-in-noise test

The speech recognition threshold in noise (SRTn) was measured using Lists 1 and 2 from the Danish hearing-in-noise test (HINT) [11]. The task was to repeat sentences presented binaurally. The answer was registered as "correct" or "false" by the experimenter. The noise level was fixed at 65 dB SPL. The first sentence was presented at zero-dB speech-to-noise-ratio. The speech level was

changed according to a one-up one-down rule. The SRT<sub>n</sub> was the mean of speech levels in the 15 last sentences minus the noise level. The SRT<sub>n</sub> was measured in two different noise types: a stationary speech-shaped noise and a fluctuating background, the International Speech Test Signal. Condition and list order were randomised.

#### International outcome inventory – hearing-aid

Six weeks after HA fitting, the HI listeners received the Danish international outcome inventory – hearing-aid (IOI-HA) [12] to evaluate the HA intervention. It consists of seven items divided into two subscales: one evaluating the introspective aspects of the HA treatment and the other evaluating interaction with the surroundings. According to a new revision of the Danish translation, item 5 was omitted [13].

#### Statistical analysis

The Pearson correlation coefficient was calculated between all test outcomes and the low (0.25, 0.5, 1 kHz) or high (2, 4, 6 kHz) pure-tone average (PTA). For the F&T test, correlations were calculated between the masking releases (MRs) and pure-tone hearing thresholds at 500 Hz after pooling the data from both ears. For the IPD detection and HINT, the average PTA from the right and left ear was used in the correlation analysis. Fisher's transformation was used to calculate the confidence interval (CI) for the correlation coefficient. Correlations between test outcomes and the IOI-HA subscales were obtained in the same manner.

*Trial registration:* The protocol was approved by the Science Ethics Committee of the Capital Region of Denmark (reference H-3-2013-004).

## RESULTS

### Group differences

**Figure 2** shows the auditory-profile test results for the HI and NHT groups. No significant difference between HI and NHT listeners was found in the reading span (RS) test (**Figure 2A**). In the F&T test, no significant difference in spectral MR was found between the two groups. However, temporal MR was significantly higher ( $p < 0.001$ , Wilcoxon rank sum test) for NHT than for HI listeners (**Figure 2B**). There was no significant group difference in terms of the upper frequency limit for IPD detection (**Figure 2C**). Concerning the ability to take advantage of fluctuating noise for speech understanding in noise, the HINT MR ( $MR_{\text{HINT}}$ ) was significantly higher ( $p < 0.001$ , Wilcoxon rank sum test) in NHT than in HI listeners.

### Test battery outcome correlations with the audiogram

**Table 2** (upper rows) lists the correlation coefficient CIs between measures from each test and the PTA at high and low frequencies. Only  $MR_{\text{HINT}}$  was significantly correlated to low-frequency PTA. Outcomes from the RS, F&T and IPD detection tests were not correlated with audibility.

### Test battery outcome correlations with HA satisfaction

**Table 2** (lower rows) lists the correlation coefficient CIs between IOI-HA and all test outcomes. A significant negative correlation was found between  $MR_{\text{HINT}}$  and the introspection subscale, also when controlling for PTA, indicating that HI listeners who had only limited advantage from fluctuating noise experienced a greater HA satisfaction. Neither audibility nor other test outcomes were correlated with HA satisfaction.



TABLE 1

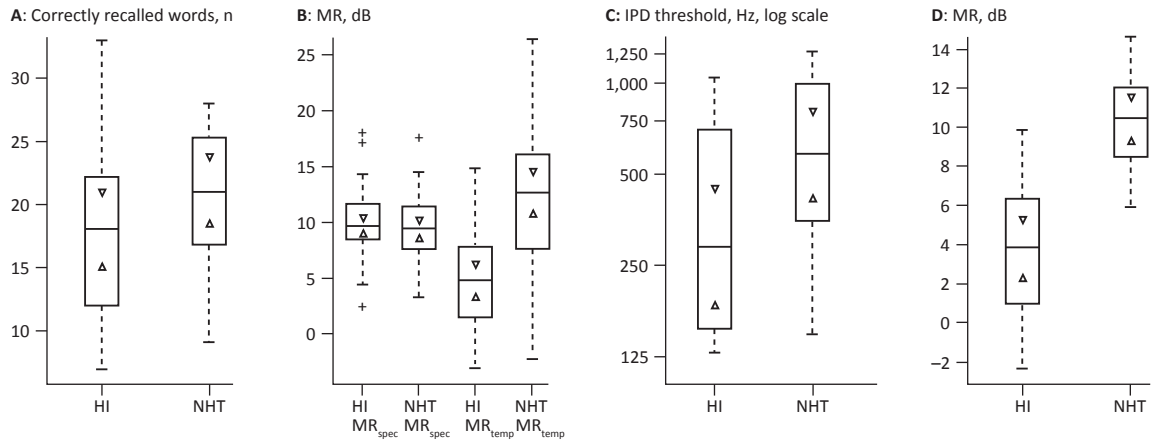
Tests included in the test battery and corresponding outcomes and interpretation of the outcomes.

Domain	Test	Outcome; unit	Interpretation
Audibility	Pure-tone hearing thresholds	PTA <sub>low</sub> : 0.25, 0.5, 1 kHz; dB HL PTA <sub>high</sub> : 2, 4, 6 kHz; dB HL	–
Working memory	RS	Correct words; n	High number of recalled words indicates good working memory capacity
Spectral and temporal resolution	F&T-test	MR <sub>spec</sub> : MR no gap vs. spectral gap; dB MR <sub>temp</sub> : MR no gap vs. temporal gap; dB	High release of masking indicates good ability in spectral and/or temporal resolution
Binaural TFS processing	IPD detection	Upper frequency limit for IPD detection; Hz	High frequency limit indicates good TFS processing
Speech recognition in noise	Danish HINT	$MR_{\text{HINT}}$ : MR stationary vs. fluctuating noise; dB	High MR indicates good ability to make use of fluctuations in background noise in terms of speech intelligibility
HA treatment evaluation	IOI-HA	Introspection subscale; score Interaction subscale; score	Higher score indicates greater HA satisfaction

F&T = combined spectral and temporal resolution; HA = hearing-aid; high = high-frequency; HINT = hearing-in-noise test; HL = hearing level; IOI = international outcome inventory; IPD = interaural-phase-difference; low = low-frequency; MR = masking release; PTA = pure-tone average; RS = reading span; spec = spectral; temp = temporal; TFS = temporal fine structure.

FIGURE 2

Box-plot test results for reading span (A), combined spectral and temporal resolution test (B), interaural phase difference (IPD) detection (C), and hearing-in-noise test (D) for hearing impaired (HI) and near-normal hearing thresholds (NHT) listeners. Median values between 25th and 75th percentiles and extension to the most extreme data points. Δ: comparison intervals for medians:  $p < 0.05$  if the comparison intervals do not overlap.



MR = masking release; spec = spectral; temp = temporal.

DISCUSSION

The mean scores of HI and NHT listeners in the RS test did not differ. This is consistent with previous findings [8, 10]. No correlation between RS score and hearing thresholds was found here, which contrasts with an earlier study in which a significant negative correlation was found [8]. In that study both the RS score and hearing thresholds were also correlated with age, such that age could have been the determining factor. Working memory could also influence the HI listeners' ability to use the HA. However, no correlation was found here between RS score and HA satisfaction.

No correlation was found between spectral and

temporal MRs in the F&T test and hearing thresholds [9]. This finding was in contrast with an earlier study [14]. Our study used a slightly different set-up aiming to make the test more independent of test frequency, which may partly account for the different findings. The obtained significant difference between NHT and HI listeners in temporal MR is consistent with previous studies [7, 14, 15]. The lack of correlation with hearing thresholds could indicate that temporal resolution is an important non-audibility-related skill that should be taken into account when making a hearing profile.

The obtained mean frequency limit for IPD detection was much lower than in other studies [10, 16]. FTS

TABLE 2

95% confidence intervals and p-values for correlation coefficients between pure-tone average and all tests (upper half) and international outcome inventory – hearing-aid subscales and all tests (lower half).  $p < 0.05$  is considered significant.

	PTA <sub>low</sub> <sup>a</sup>	PTA <sub>high</sub> <sup>b</sup>	RS score	MR <sub>spec</sub>	MR <sub>temp</sub>	IPD	MR <sub>HINT</sub>
<i>Audiogram</i>							
PTA <sub>low</sub> :							
95% CI	–	–	–0.38-0.35	–0.33-0.27	–0.53-0.03	–0.17-0.56	–0.73–0.17
p-value	–	–	0.94	0.83	0.08	0.25	< 0.01
PTA <sub>high</sub> :							
95% CI	–	–	–0.34-0.39	–	–	–	–0.37-0.36
p-value	–	–	0.9	–	–	–	0.99
<i>IOI-HA</i>							
Introspection:							
95% CI	–0.05-0.64	–0.37-0.39	–0.50-0.25	–0.27-0.33	–0.19-0.41	–0.51-0.29	–0.79–0.26
p-value	0.08	0.94	0.46	0.83	0.46	0.54	< 0.01
Interaction:							
95% CI	–0.28-0.47	–0.53-0.20	–0.56-0.17	–0.28-0.34	–0.33-0.30	–0.09-0.64	–0.45-0.31
p-value	0.57	0.34	0.26	0.83	0.92	0.12	0.69

CI = confidence interval; HA = hearing-aid; high = high-frequency; HINT = hearing-in-noise test; IOI = international outcome inventory; IPD = interaural-phase-difference; low = low-frequency; MR = masking release; PTA = pure-tone average; RS = reading span; spec = spectral; temp = temporal.

a) At 0.25, 0.5, 1 kHz.

b) At 2, 4, 6 kHz.

processing is known to decrease with age [17]. All listeners in our study were more than 40 years old, which could explain the lower limits and the lack of group difference. The present results are consistent with previous findings of no correlation between low-frequency hearing thresholds and IPD detection thresholds in HI listeners [10, 17]. Thus, the findings support that binaural TFS-processing abilities decrease with age and are independent of audibility.

MR<sub>HINT</sub> was significantly negatively correlated with low-frequency hearing thresholds, suggesting that although low-frequency audibility may not be the sole factor, it does play a role in speech perception in fluctuating noise. However, audibility was not correlated with HA satisfaction, whereas MR<sub>HINT</sub> was. This suggests that pure-tone hearing thresholds are not a crucial factor for HA satisfaction, while the ability to “listen in the dips” of background noise might be a better predictor. By examining whether MR<sub>HINT</sub> was correlated with other psychoacoustic measures, we found a significant correlation with temporal MR in the F&T test ( $r = 0.477$ ;  $p = 0.029$ ). This is consistent with a recent study which also found such a correlation [18]. Therefore, both temporal resolution and audibility may independently influence the ability to benefit from fluctuations in background noise, and thus HA satisfaction.

Previous studies have also investigated how audibility was related to IOI-HA outcome. One study found a positive correlation between hearing thresholds and items 1 and 4 and a negative correlation between hearing thresholds and item 6 [13]. Another study found no such correlations [19]. In contrast to the former study [13], the latter [19] and the present study only included listeners with sensorineural hearing loss, which may partly explain the different findings. If, as found here, hearing thresholds do not correlate with HA satisfaction, it is questionable to use the audiogram as the only key measure for HA fitting.

Finally, satisfaction in listening situations “conversation with one person”, “in a small group”, “in larger groups”, and “outdoors” was previously found to be important to receive a high IOI-HA outcome [20]. This is consistent with the present study’s finding that the ability to benefit from fluctuations in noise is related to IOI-HA outcome. However, as many factors are known to influence IOI outcome, caution is advised when drawing conclusions from the IOI-HA, and the questionnaire may be too general to be directly related to specific psychoacoustic measurements.

## CONCLUSION

The tested auditory profile confirmed that HI listeners have difficulties in different hearing domains that are not predictable from their audiogram. Specifically, tem-

poral resolution and low-frequency hearing thresholds were found to be related to speech recognition in fluctuating versus stationary noise. Hearing-impaired listeners, who had a more limited intelligibility advantage from fluctuations in the background noise, experienced greater HA satisfaction. Neither hearing thresholds nor other test outcomes were correlated with HA satisfaction. Measures of temporal resolution or speech perception in both stationary and fluctuating noise could be relevant measures to consider in an extended auditory profile. However, further large-scale studies are needed to examine how such an extended clinical auditory profile should be related to HA fitting procedures. A more objective evaluation of HA benefit would also be an important step forward.

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**CONFLICTS OF INTEREST:** Disclosure forms provided by the authors are available with the full text of this article at [www.danmedj.dk](http://www.danmedj.dk)

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