Evaluation of a clinical auditory profile in hearing-aid candidates

NICOLINE THORUP[1,*], SÉBASTIEN SANTURETTE[2], SØREN JØRGENSEN[2], ERIK KJÆRBØL[1], TORSTEN DAU[2], AND MORTEN FRIIS[1,3]

[1] *Department of Otorhinolaryngology and Audiology, Rigshospitalet, Denmark*

[2] *Hearing Systems, Department of Electrical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark*

[3] *University of Copenhagen, Copenhagen, Denmark*

Hearing-impaired (HI) listeners often complain about 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, such that people with similar audiograms are given the same prescription by default. However, this does not necessary lead to the same HA benefit. This study aimed at identifying clinically relevant tests that may be informative in addition to the audiogram and relate more directly to HA benefit. Twenty-nine HI listeners performed fast tests of loudness perception, spectral and temporal resolution, binaural hearing, speech intelligibility in stationary and fluctuating noise, and a working-memory test. Six weeks after HA fitting they answered the International Outcome Inventory – Hearing Aid evaluation. The HI group was homogeneous based on the audiogram, but only one test was correlated to pure-tone hearing thresholds. Moreover, HI listeners who took the least advantage from fluctuations in background noise in terms of speech intelligibility experienced greater HA benefit. Further analysis of whether specific outcomes are directly related to speech intelligibility in fluctuating noise could be relevant for concrete HA fitting applications.

INTRODUCTION

It has been estimated that 30% of Danish hearing-aid (HA) users found listening situations to improve only moderately, a little bit, or not at all after HA prescription (Jørgensen, 2009), suggesting inadequate HA treatment. Pure-tone audiometry typically forms the basis for administering and fitting HA devices. This implies that people with similar audiograms are given the same HA prescription by default. However, patients with the same audiometric profile may experience differences in HA benefit.

Although audibility may be restored by a HA, users often complain about communicating in the presence of background noise. Previous studies have shown

*Corresponding author: nicolinethorup13@gmail.com

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that the audiogram correlates well with speech intelligibility in quiet but poorly with speech intelligibility in noise (Festen and Plomp, 1983; Glasberg and Moore, 1989). Moreover, hearing-impaired (HI) listeners with normal or near-normal pure-tone hearing thresholds at low frequencies may show speech identification deficits when the speech spectrum is limited to the regions of normal or near-normal hearing (Léger *et al.*, 2012). Speech intelligibility in noise has also been found to correlate with temporal fine-structure (TFS) processing abilities reflected by, e.g., frequency discrimination (Festen and Plomp, 1983; Papakonstantinou *et al.*, 2011), and TFS processing deficits can be present despite near-normal thresholds (Strelcyk and Dau, 2009). The evaluation of a test battery covering different hearing domains, hearing disability, listening effort, and cognitive function recently showed that HI listeners can suffer from auditory deficits that do not necessarily correlate with the audiogram but may be detectable in clinically-applicable tests (van Esch *et al.*, 2013).

Despite compelling evidence that the audiogram alone is insufficient to characterize 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 this study was to evaluate whether a clinical auditory profile including different psychoacoustics tests and a cognitive test 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 benefit in relation to the auditory profile to investigate if specific test outcomes relate to HA benefit.

METHODS

Listeners

Twenty-nine HI listeners with sensorineural high-frequency hearing loss (age 52-80 years, mean 68.4, 13 female, 8 new and 21 experienced HA users) participated. The inclusion criteria were based on predefined audiometric categories (Bisgaard *et al.*, 2010). At low frequencies, the categories “mild” to “moderate” hearing loss were included. At high frequencies, the categories “mild” to “moderate/severe” hearing loss were included. A maximal deviation from these categories of +/- 5 dB at each frequency was allowed, except at 250 Hz and 500 Hz where no lower limits were defined. All HI listeners had bilateral HA therapy and were native Danish speakers. Listeners were excluded if they suffered from asymmetry > 15 dB hearing level (HL) at any frequency, or asymmetry in speech discrimination (DS) > 20%, or if they suffered from conductive hearing loss.

Experimental set-up

All measurements were conducted via a PC in a double-walled soundproof booth. The stimuli were generated in MATLAB and presented via a Fireface UCX sound card connected to Sennheiser HDA200 headphones. Calibration was performed using a B&K 2636 measuring amplifier and a B&K 4153 artificial ear simulator. 128-tap linear phase FIR equalization filters were applied to all broadband stimuli to flatten the headphone frequency response. For audiometric 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 250-8000 Hz were measured. The test battery was always scheduled for another day than pre-examination and HA fitting. A standardized written and verbal introduction was given before each test and all tests contained a training run. The cognitive test was carried out before the psychoacoustic measurements, which sequence was randomized. All hearing tests were conducted without HA.

The test battery

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

Domain	**Test**	**Outcome**
Audibility	Pure-tone hearing thresholds	PTA_{low}: 0.25, 0.5, 1 kHz (dB HL) PTA_{high}: 2, 4, 6 kHz (dB HL)
Working memory	Reading span	Number of correct words
Spectral and temporal resolution	Combined spectral and temporal resolution test (F&T-test)	MR no gap vs. spectral gap (dB) MR no gap vs. temporal gap (dB)
Binaural TFS-processing	Interaural-phase-difference (IPD) detection	Upper frequency limit for IPD detection (Hz)
Speech perception in noise	Danish hearing-in-noise test (HINT)	MR stationary vs. fluctuating noise (dB)
Hearing-aid treatment evaluation	The “international-outcome-inventory – hearing-aid” (IOI-HA)	Score on introspection subscale Score on interaction subscale

Table 1: Tests included in the test battery and corresponding outcomes.

Reading span (RS). The reading span test was used to evaluate working memory storage and processing simultaneously (Lunner, 2003). The main task was to recall the first or the final word in a sequence of sentences. The remembered words were pronounced out loud and the test contributor registered the answers. The secondary task was to assess continuously if each sentence was correct or absurd. The participant responded by pressing the keyboard “F” (absurd) or “K” (correct) after each sentence. A total of 54 sentences (27 correct and 27 absurd) were presented. The outcome measure was the number of correctly recalled words (RS score).

Combined spectral and temporal resolution. Auditory spectral and temporal resolution were tested simultaneously using a modified version of the F&T test (Larsby and Arlinger, 1998). The task was to detect a pulsed tone at 500 Hz in the presence of broadband threshold-equalizing noise (TEN; Moore *et al.*, 2000) containing either no gap, a spectral gap, or a temporal gap. The tone length was 275 ms and the tone-pulse-interval 175 ms with a 50-ms ramp. The spectral gap was 3 equivalent rectangular bandwidths wide around the center frequency and the temporal gap around the pulsed tone was of 50-ms duration. The noise level was fixed at 55 dB SPL. The tone level was varied adaptively using a Békésy tracking method with a starting value of 70 dB SPL. Each condition was measured monaurally in the left and right ear. The sequence of noise conditions and ears was randomized. All conditions were measured twice. Masking releases (MRs) between the spectral-gap and no-gap (MR_{spec}) and temporal-gap and no-gap (MR_{temp}) conditions were calculated.

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 (Ross *et al.*, 2007), using a procedure similar to Santurette and Dau (2012). 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 modulation rate at 40 Hz and modulation depth equal to 1. The presentation level was 35 dB sensation level defined from the pure-tone hearing-thresholds for each ear separately. The start frequency was 250 Hz. The frequency changed according to a 2-up 1-down rule. The frequency was changed in step-sizes of 1/2, 1/5, and 1/10 octave that decreased after each lower reversal. Two measurements were obtained for each listener.

Hearing-in-noise test. The speech reception threshold in noise (SRTn) was measured using the Danish hearing-in-noise test (HINT; Nielsen and Dau, 2011). The listener was asked to repeat the presented sentences and the answer was registered as “correct” or “false” by the test instructor. The noise was set at a fixed level of 65 dB SPL. The first sentence was presented at 0-dB speech-to-noise-ratio (SNR). The speech level was changed according to a 1-up 1-down rule. The SRTn was the mean of speech levels in the 15 last sentences minus the noise level. SRTn was measured in two different noise types: a stationary speech-shaped noise and a fluctuating background, the International Speech Test Signal (Holube *et al.*, 2010). Lists 1 and 2 from the Danish HINT sentences were used. Condition and list order were randomized. The masking release between SRTn in stationary and fluctuating noise (MR_{HINT}) was calculated.

International Outcome Inventory – Hearing Aid. To evaluate the benefit from the HA intervention the HI listeners answered the Danish IOI-HA (Jespersen *et al.*, 2006). The IOI-HA consists of 7 items and is divided into two subscales. One subscale evaluates the introspective aspects of the HA treatment and the other interaction with the surroundings. According to a new revision of the Danish translation, item 5 was omitted (Jespersen *et al.*, 2014). The greater the advantage a person has from the HA, the greater the score is in the IOI-HA evaluation.

RESULTS

The Pearson correlation coefficient was calculated between the outcomes of all tests and the low (0.25, 0.5, 1 kHz) and/or high (2, 4, 6 kHz) pure-tone average (PTA). For the F&T test, correlations were calculated between the masking releases (MRs) and the pure-tone hearing thresholds at 500 Hz after pooling the data from both ears. For the IPD detection and HINT tests, 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 way.

Correlations with the audiogram

Table 2 (upper rows) lists the correlations coefficient CIs between measures from each test and the PTA at high and low frequencies. Scatter plots of the individual outcomes for each test as a function of audibility are also given in Fig. 1. Only the MR_{HINT} was significantly correlated to PTA at low frequencies. Outcomes from the reading span, F&T test, and IPD detection test were not correlated to audibility.

Correlations with HA benefit

Table 2 (lower rows) lists the correlations coefficient CIs between IOI-HA and outcome measures from all tests. A negative significant correlation was found between the MR_{HINT} and the introspection subscale (also when controlled for PTA), indicating that HI listeners who took small advantage in fluctuating noise experienced a greater HA benefit. Neither audibility nor other test outcomes were correlated with HA benefit.

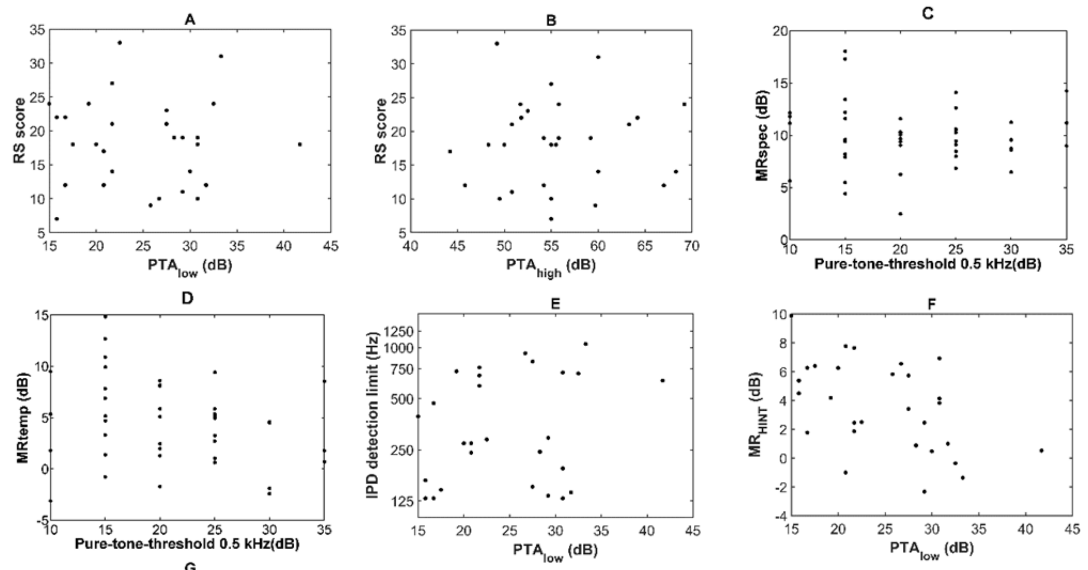
DISCUSSION

Comparison to earlier findings

In the present study an extended auditory profile was tested on a group of HA users. In the following, the results are compared to findings from previous studies.

		PTA_{low}	PTA_{high}	RS score	MR_{spec}	MR_{temp}	IPD	MR_{HINT}
Audio-gram	**PTA_{low}**			[-.38;.35]	[-.33;.27]	[-.53;.03]	[-.17;.56]	**[-.73;-.17]**
	p-value			*.94*	*.83*	*.08*	*.25*	***<.01***
	PTA_{high}			[-.34;.39]				[-.37;.36]
	p-value			*.90*				*.99*
IOI-HA	**Introspection**	[-.05;.64]	[-.37;.39]	[-.50;.25]	[-.27;.33]	[-.19;.41]	[-.51;.29]	**[-.79;-.26]**
	p-value	*.08*	*.94*	*.46*	*.83*	*.46*	*.54*	***<.01***
	Interaction	[-.28;.47]	[-.53;.20]	[-.56;.17]	[-.28;.34]	[-.33;.30]	[-.09;.64]	[-.45;.31]
	p-value	*.57*	*.34*	*.26*	*.83*	*.92*	*.12*	*.69*

Table 2: Confidence intervals and *p*-values for correlation coefficients between PTA and all tests (first 4 rows) and IOI-HA subscales and all tests (last 4 rows). PTA_{low} at 0.25, 0.5, 1 kHz; PTA_{high}: PTA at 2, 4, 6 kHz.



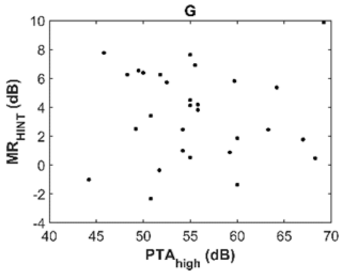


Fig 1: Scatter plots of the individual data as a function of hearing thresholds (dB HL). A: RS score vs. PTA$_{low}$; B: RS score vs. PTA$_{high}$; C: MR$_{spec}$ vs 500-Hz threshold; D: MR$_{temp}$ vs 500-Hz threshold; E: IPD detection limit vs. PTA$_{low}$; F: MR$_{HINT}$ vs PTA$_{low}$; G: MR$_{HINT}$ vs PTA$_{high}$.

Correlations with the audiogram. One earlier study found significant negative correlation between the reading span score and audibility (Lunner, 2003). However, in that study, both the RS score and hearing thresholds were also correlated with age, such that age could have been the determining factor. While no correlation of spectral and temporal masking releases in the F&T test with hearing thresholds was at first found (Larsby and Arlinger, 1998), a second study found a significant correlation (Larsby and Arlinger, 1999). The present study, which used a slightly different set-up aiming to make the test more independent of test frequency, showed no correlations with audibility. The present results are consistent with previous findings of absent correlation between low-frequency hearing thresholds and IPD detection thresholds in HI listeners (Santurette and Dau, 2012, Füllgrabe and Moore, 2014). The correlation between the Danish HINT and PTA was not previously examined. Here, the SRTn in stationary noise was correlated with PTA$_{high}$ ($p<0.01$) and SRTn in fluctuating noise with PTA$_{low}$ ($p<0.05$), and the MR between the two with PTA$_{low}$.

Correlations with HA benefit. Previous studies have investigated how audibility, demographic factors, HA type and fitting were related to the IOI-HA outcome. A positive correlation between hearing thresholds and items 1 and 4 and a negative correlation between hearing thresholds and item 6 were found in Jespersen *et al.* (2014). It was also found that more severe hearing impairment, previous HA experience, and bilateral fitting were significantly correlated to a higher score on the introspection subscale and a lower score on the interaction subscale (Jespersen *et al.*, 2006). In a recent study, no correlations were found between hearing thresholds, HA experience, and IOI-HA outcome (Brannstrom *et al.*, 2014). Predictions of IOI-HA outcome were also investigated by taking demographic factors and the audiogram into account. Only the DS of the better ear was found to predict 16% of the interaction sub-scale. Potential confounders could be age, poor audibility, and poorer SRT, because all these factors were related to the DS of the better ear. The IOI-HA measures HA satisfaction in general. Satisfaction in listening situations “conversation with one person”, “in small group”, “in larger groups”, and “outdoors” were found to be important to receive a high IOI-HA outcome (Hickson *et al.*, 2010). This is consistent with the present finding that hearing in fluctuating noise is related to the IOI-HA outcome. Many factors influence IOI-outcome and the questionnaire may be too general to be directly related to specific psychoacoustic measurements in a clinical test battery. Moreover, etiological details of the hearing impairment such as family history and known genetic factors were not considered in the present study although they may play a role in differences in HA outcome in patients with similar audiometric profiles. These aspects would thus be relevant to consider in an extended hearing profile, as they may shed light on where damage is located along the auditory pathway.

Clinical feasibility

All tests were conducted in one session. A short training session and maximally two repetitions were performed. The set-up was comparable to a clinical setting. All participants were able to complete the test battery. The test set up was easily implementable as only a PC, headphones, and soundcard were needed. The duration time of the complete test-battery would have to be brought down for clinical implementation. However, only the F&T-test had a duration time above 20 minutes.

CONCLUSION

The tested auditory profile confirmed that HI listeners have difficulties in different hearing domains that are not predictable from their audiogram. The ability to make use of temporal fluctuations in background noise in terms of speech intelligibility was the only outcome measure directly related to subjective HA benefit. However, such a measure was also related to low-frequency audibility, although HA benefit was not. Further analysis of whether other specific outcomes are directly related to speech intelligibility in fluctuating noise could be relevant for concrete HA fitting applications. A large-scale evaluation of the test battery in relation to more objective measures of HA fitting and aided listening performance, as well as further reductions in testing time, are steps forward to select the key tests that would be beneficial in clinical hearing assessment.

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