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Hearing in the Communication Society

INTEGRATED PROJECT

Information Society Technologies

D-2-6: Report about the results of the multi-centre evaluation of the Auditory Profile

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Pre-Amble

This deliverable concerns the results of the validation of the auditory profile that has been defined in deliverable D-2-4, by a multi-centre experimental approach. This is the second stage of validation, following on from the first stage reported in D-2-3. The second stage used a shortened and improved version of the auditory profile, based on the first stage analysis. The protocol for the second stage multi-centre study has been described in deliverable D-2-5. The auditory profile is designed in order to enable consistent characterization of an individual's auditory impairment across Europe. It is intended that the auditory profile can be used to determine individual hearing deficiencies in communication and can subsequently help to determine the benefit from assistive devices. The auditory profile should include key measures to characterise similarities and differences among various hearing impairments.

The auditory profile is relevant for the work in SP2 (Adverse Conditions), because its outcome values will define the auditory demands for the acoustical conditions required in case of hearing impairment. The work is relevant for SP3 (Rehabilitation) and SP4 (Assistive Technology), because the auditory profile indicates the deficits that need to be compensated, either by signal processing (SP3) or by alternative strategies (SP4). Finally, the implementation of these tests in OMA (Oldenburg Measurement Applications) will have an impact on the dissemination of the test procedures and will potentially stimulate broad clinical acceptance of this innovative approach to auditory testing.

1 Executive Summary

The HEARCOM (Hearing in the Communication Society) project aims at full participation in the modern communication society by reducing the limitations in auditory communication. Two of the focus areas of HEARCOM are on the identification and characterization of auditory communication limitations and on the development of standardized testing and evaluation procedures for hearing-impaired persons. In this context, a preliminary auditory profile was defined and then modified on the basis of a first stage evaluation (D-2-3). This preliminary auditory profile was previously validated in an international multi-centre study. The present study comprises the second stage of validation, again in an international multi-centre study. The results of that study are presented in the current report.

The aim of the auditory profile is that it should be used as a diagnostic tool in a broad population of subjects with complaints about their performance in (auditory) communication tasks. It will be a diagnostic profile that can be assessed in a (specialized) hearing centre or clinic or in audiological research. The end user of the auditory profile is intended to be the professional interested in the characteristics of the hearing of a particular client/patient and comparisons with reference data.

The focus of the multi-centre field trial was to investigate the intrinsic characteristics of the profile with a view to its clinical applicability. All tests were implemented in OMA (Oldenburg Measurement Applications) software. For applications in research, the software can be left more open in order to be flexible towards diverging applications. However, for clinical use the test procedures should be described in detail and the software should obtain a CE-approval in due time.

In the present deliverable, results of the second stage multi-centre study are presented. The data comprised measurements from 26 normal hearing (NH) and 102 hearing impaired (HI) listeners with symmetrical sensorineural hearing loss in the range from mild to severe.

- First we investigated the distributions of the test measures and compared NH and HI listeners.
- Next we examined relationships among measures obtained separately for the right and left ears by factor analysis and multiple linear regression. The aim was to identify groups of variables that formed factors and to derive regression models for predicting speech recognition performance in noise.
- Subsequently we did the same for binaural measures, including better-ear values and measures of asymmetry for the variables

measured separately for right and left ears. The aim was to identify factors and to predict binaural performance on speech recognition tasks.

- Finally we did the same for self-reported communication difficulty measures.

Based on these results, the following broad conclusions emerged.

- Speech recognition performance in noise can be predicted well from conventional audiometric measures: specifically the audiogram and age. The average of the thresholds at 0.5, 1, 2 and 4 kHz, which has been used in many other studies to summarise hearing impairment, is nearly as good a predictor as a linear combination of all the conventional thresholds.
- Prediction of speech recognition performance in noise is improved by the addition of a measure of spectral resolution at 0.5 kHz, especially for speech in fluctuating noise and when speech and noise are spatially separated.
- It follows that for clinical purposes there is little to be gained from more complex psychoacoustic characterisation of sensorineural hearing impairment, when the purpose is to predict or explain difficulty understanding speech in noise. A conventional audiogram and possible measurement of spectral resolution at 0.5 kHz is sufficient.

2 Introduction

2.1 Brief overview protocol

2.1.1 Tests

We agreed on the following tests to be included in the stage 2 evaluation of the auditory profile. The tests are described in more detail in D-2-5, which should be read in conjunction with this report.

Table 1: List of tests included in the stage 2 auditory profile

Characteristic	**Test**	**Details**
Audibility	Audiogram	air conduction: .25/.5/1/2/3/4/6/8 kHz bone conduction: .25/.5/1/2/3 kHz
Loudness perception	Acalos	500 Hz 3000 Hz
Frequency-time resolution	FT test	500 Hz 3000 Hz
Speech perception	SRT with short meaningful sentences	in quiet (binaural) in stationary noise (monaural) in fluctuating noise (monaural)
Binaural processing	ILD	SRT with matrix-type sentences
	BILD	SRT with matrix-type sentences
Cognitive abilities	Lexical Decision Making	
Self-reported hearing difficulty	Gothenburg Profile	

All these tests have been implemented on a common software platform in Oldenburg (OMA, Oldenburg Measurement Applications), see deliverable D-2-1b. All tests were conducted unaided, via circumaural headphones (Sennheiser HDA-200). For an extensive description of the protocol, see D-2-5.

2.1.2 Inclusion of subjects

We agreed on the following inclusion criteria:

100 Hearing-impaired subjects (20 for each of the participating centres):

- Age between 18 and 75 years.

- Average hearing loss (PTA) at the better ear between 20 and 70 dB for both ears. The average is taken from the pure tone audiogram thresholds at 0.5, 1, 2 and 4 kHz. At both ears, thresholds at 0.5 and 3 kHz (measurement frequencies) should be between 20 and 60 dB.
- Maximum difference in PTA between ears of 20 dB
- Air-bone gap (0.5-1-2-kHz average) of 10 dB or less
- No language problems.
- Active and alert and able to perform the tests.
- Willing to attend one visit for testing (about 2 hours).
- No complaints of tinnitus.

Also we planned to include 25 normal-hearing subjects (5 for each centre).

See also D-2-5 for a more detailed description of the audiometric subject categories.

2.2 Round trip

The centres were the same as those in the first stage validation and had participated in the round trip check of their set-up (see D-2-3). The same set-up was used in each centre for both stages and there were only minor differences in the test protocol. Therefore, it was decided not to repeat the round trip for the second stage.

2.3 Measurements and data-analysis

2.3.1 Included subjects

All centres were approved by their local research ethics committees for the conduct of the study, in accordance with the Declaration of Helsinki.

Table 2: Numbers of participants by centre

	AMC	**HZO**	**ISVR**	**LINK**	**VUMC**	**Total**
NH	5	6	5	5	5	26
HI	21	20	21	20	20	102
Total	26	26	26	25	25	128

2.3.2 Data analysis

The analysis plan followed the general pattern of the analysis of the first stage validation (see D-2-3), as follows.

- First we examine the distributions of all measures, comparing NH and HI groups and identifying the need for transformations where data are not normally distributed.
- Next focus on variables measured separately in right and left ears (monaural), using factor analysis and multivariate regression analysis.
- Next do the same with the binaural variables, including also better ear and asymmetry measures in the analyses.
- Finally evaluate the self-reported communication difficulty measures and their relation to the selected binaural and monaural variables.

3 Results

3.1 Outcome measures

In order to organise the large number of outcome measures, we divided them into four groups:

3.1.1.1 Monaural tests at 500 and 3000 Hz

Test	**Outcome measures**	**Abbreviation**
Audiogram:	air-conduction thresholds	Ra (right) La (left)
Loudness scaling:	most comfortable loudness level (20 CLU)	Lcut
	slope lower part of the curve	Mlo
FT test:	release of masking for spectral resolution	Spec
	release of masking for temporal resolution	Temp

3.1.1.2 Monaural tests, broadband

Test	**Outcome measures**	**Abbreviation**
Speech perception:	SRT in stationary noise	SRTstat
	SRT in fluctuating noise	SRTfluct

3.1.1.3 Binaural tests

Test	**Outcome measures**	**Abbreviation**
Speech perception:	SRT in quiet (diotic)	SRTq
Binaural processing	intelligibility level difference	ILD
	binaural intelligibility level difference	BILD
Lexical decision:	percentage correct / response time	LexDec

3.1.1.4 Self-report of communication abilities

Test	**Outcome measures**	**Abbreviation**
Gothenburg profile	Speech subscale score (%)	GPspeech
	Spatial hearing subscale score (%)	GPloc
	Social interaction subscale score (%)	GPrelation
	Behaviour and reaction subscale score (%)	GPperform

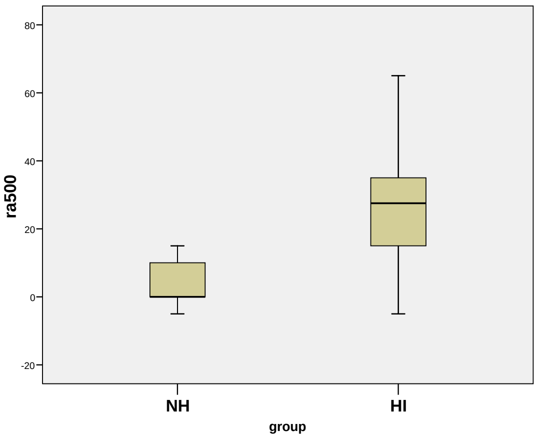
3.2 Analysis of distributions

3.2.1 Distributions of monaural measures

We start with a visual presentation (box plots), for normal-hearing and hearing-impaired listeners in separate boxes.

3.2.1.1 Audiogram

Hearing threshold levels by air conduction were analysed at frequencies of 0.5, 1, 2, 3 and 4 kHz for right and left ear. The box-plots in Fig. 1 indicate the range of hearing threshold levels for the NH and HI groups. Examination of histograms and Q-Q plots of the NH and HI groups indicated that they were approximately normally distributed.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HI
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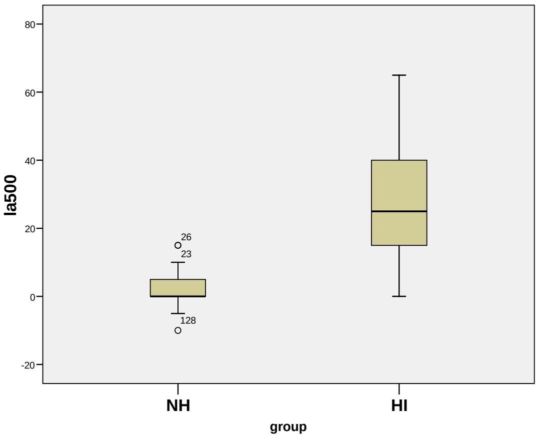
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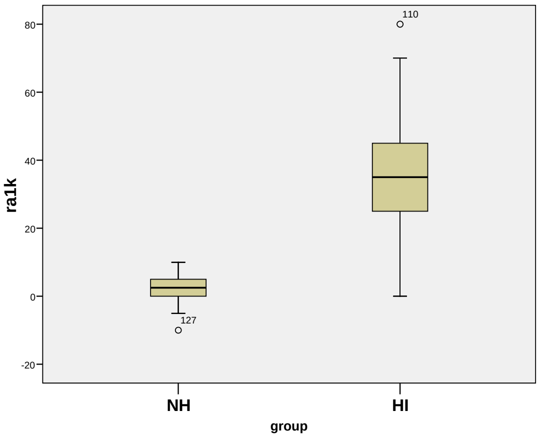
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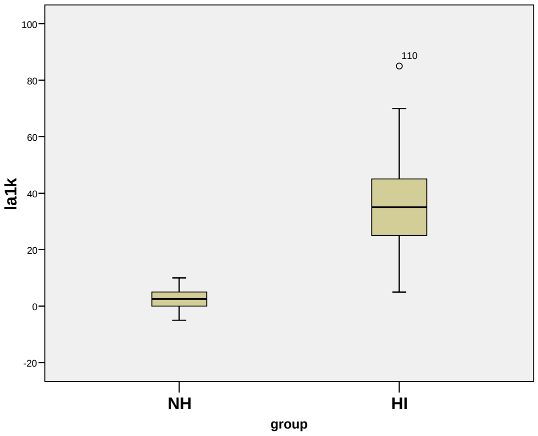
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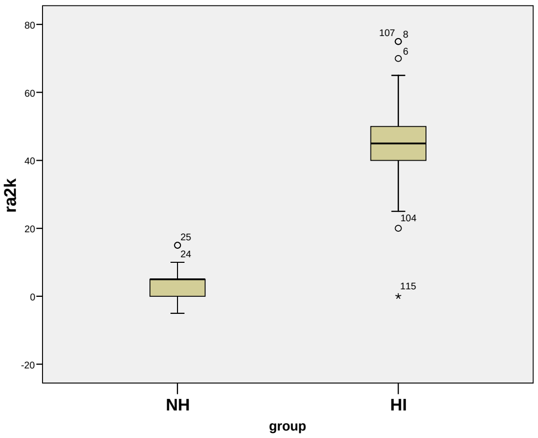
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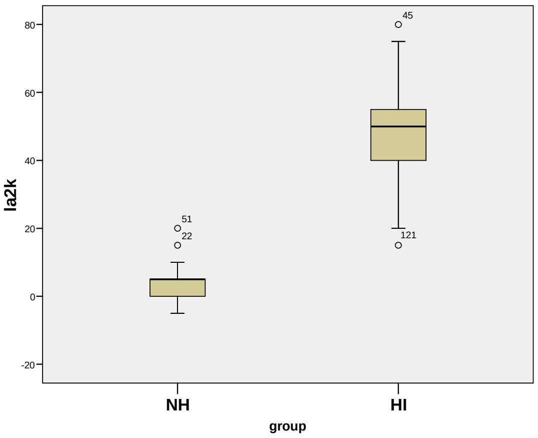
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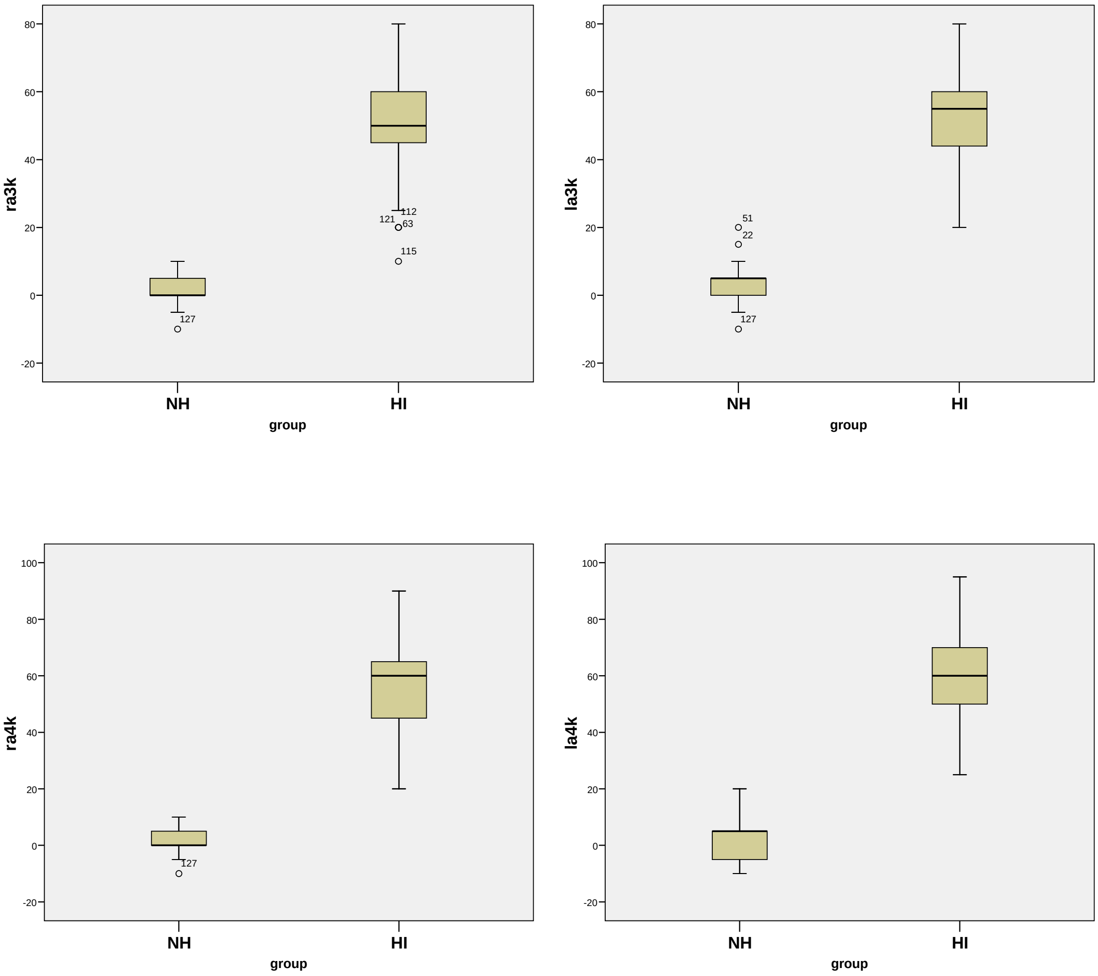
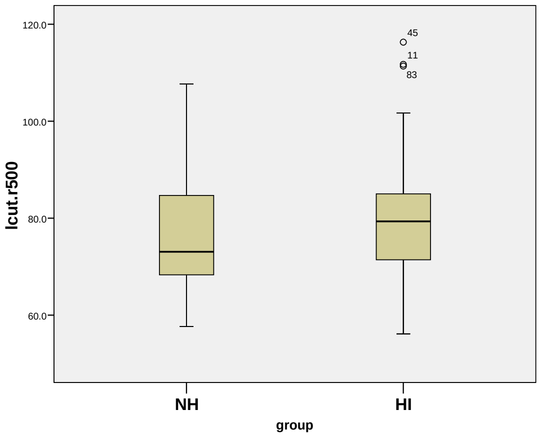
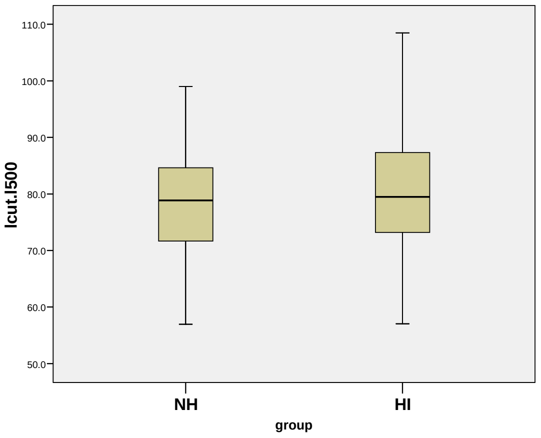


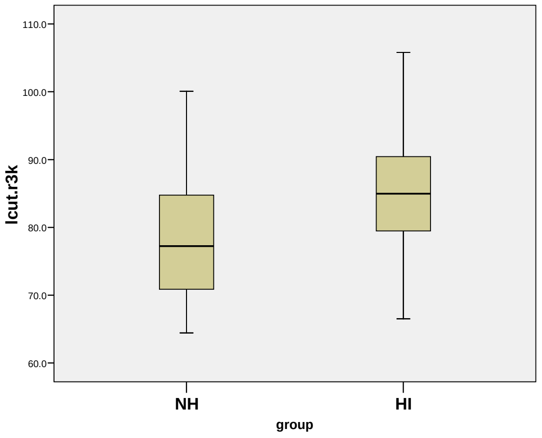
Figure 1: Air-conduction thresholds at 0.5 to 4 kHz for right ear (left panel) and left ear (right panel) in dB HL for normal-hearing and hearing-impaired listeners.

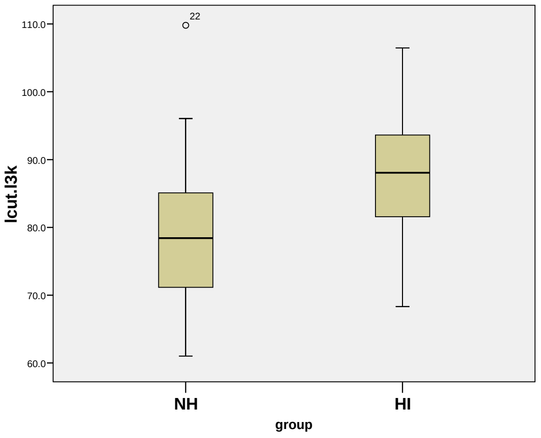
3.2.1.2 Loudness scaling (dynamic range, compression)

Loudness scaling results using the Acalos procedure are shown in Fig. 2. Two measures of loudness scaling were used for the analysis. Lcut was obtained from the ACALOS procedure and represents the knee-point on the loudness growth function and approximates the MCL level. Mlo is an estimate of the slope of the lower portion of the loudness growth function and represents low-level compression (higher values indicate more loudness recruitment). These measures were obtained for frequencies at 0.5 and 3 kHz in each ear. The following box-plots show the distribution for the NH and HI groups. Examination of histograms and Q-Q plots indicated that the measures were approximately normally distributed. There was a wide range of results for both NH and HI groups and the mean differences between groups on Lcut were small. For Mlo, there was also substantial overlap between groups but the HI group overall showed steeper loudness growth than the NH group, especially at 3 kHz. This is consistent with the presence of recruitment in the HI participants. It can be seen that in general, hearing-impaired listeners (HI) have higher MCLs and steeper slopes than normal-hearing listeners (NH). Moreover, there is more spread in the HI data than in the NH data.









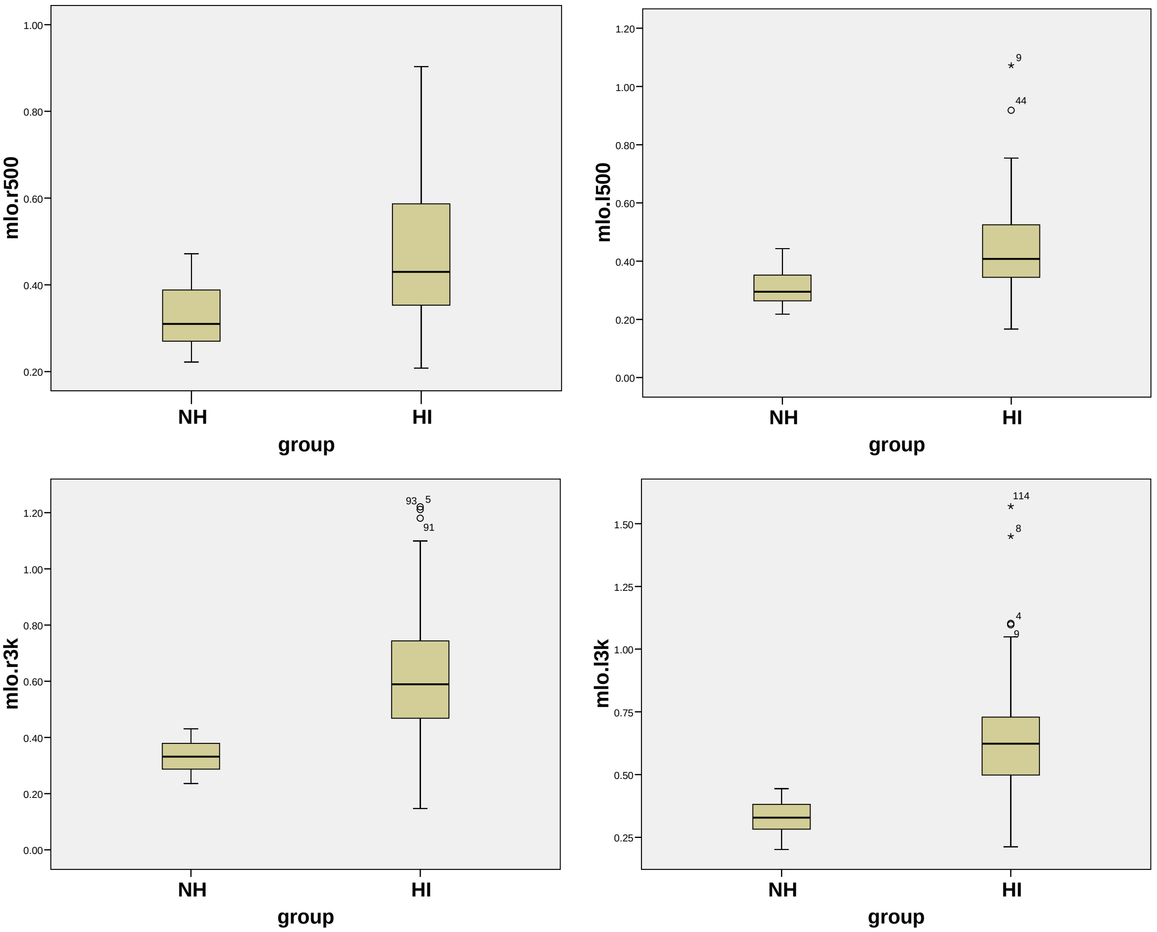
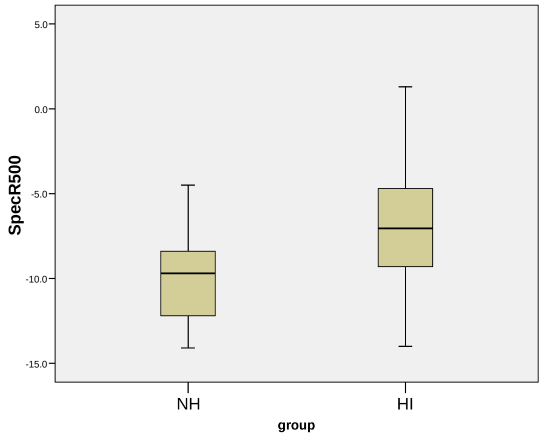


Figure 2: Measures of loudness scaling at 0.5 and 3 kHz for right ear (left panel) and left ear (right panel) for normal-hearing and hearing-impaired listeners. Lcut estimates MCL and mlo estimates the slope of the loudness growth function for lower intensities (low level compression).

3.2.1.3 Spectral and temporal resolution

Measures of frequency and temporal resolution at 0.5 and 3 kHz in each ear were obtained from the FT test. The box-plots in Fig. 3 show the distribution for the NH and HI groups. The variables prefixed “Spec” indicate spectral resolution and variables prefixed “Temp” indicate temporal resolution. Examination of histograms and Q-Q plots indicated that the measures were approximately normally distributed. It can be seen that the HI group showed poorer spectral and temporal resolution than the NH group, especially at 3 kHz. There were a few outliers, mainly with unusually good resolution for the HI group. All outliers had been double-checked for possible errors of coding or test administration, but none were found to explain the unusual results.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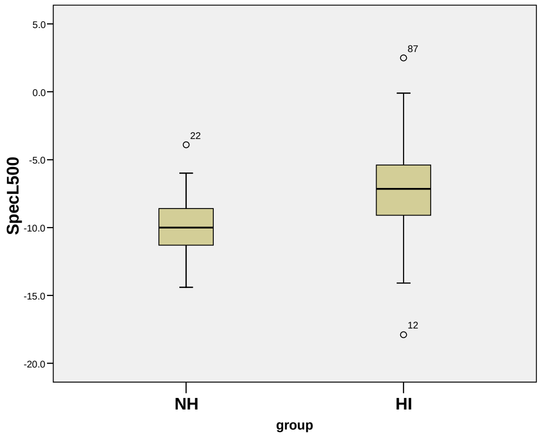
NH
HI
group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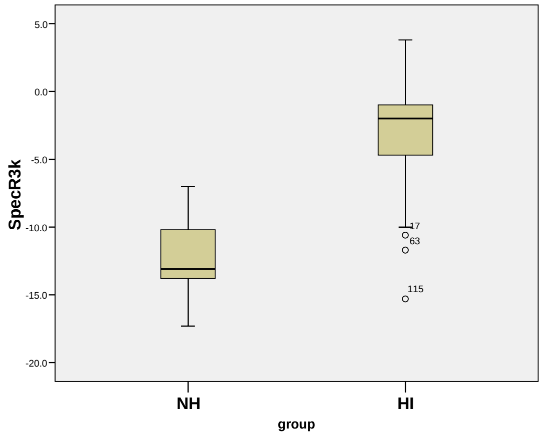
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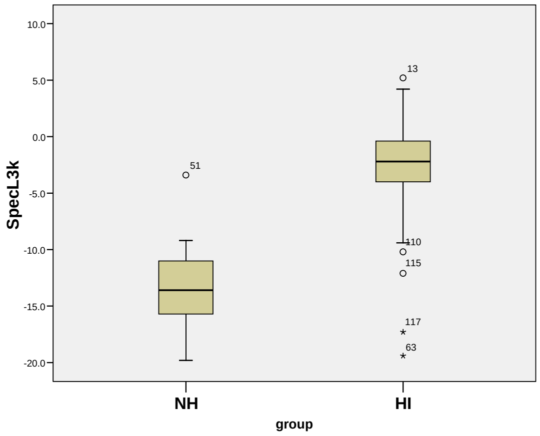
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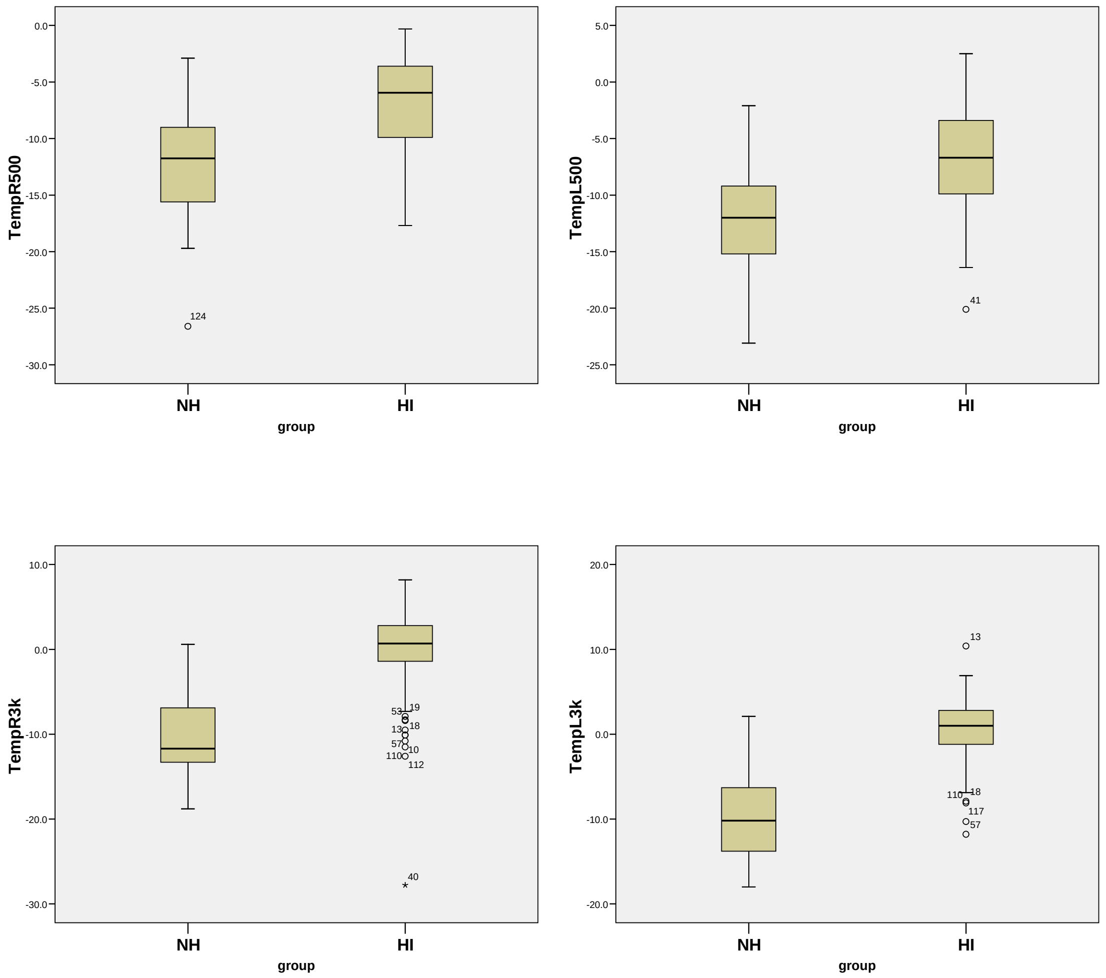

Figure 3: Measures of spectral and temporal resolution at 0.5 and 3 kHz for right ear (left panel) and left ear (right panel) for normal-hearing and hearing-impaired listeners.

3.2.1.4 Speech recognition in noise

Speech recognition in noise was measured using short meaningful sentences in the language corresponding to each centre. Two noise types were tested: stationary ICRA1 (or ICRA1_female) and fluctuating ICRA5 (or ICRA4_250) noise. In each case, the measure obtained was the speech-to-noise ratio (SNR) in dB corresponding to 50% correct recognition of the sentences. As there were differences in results for the NH groups across centres (languages), all results were adjusted to obtain a value relative to the mean for the stationary noise for the NH group of the centre. In this way, the results can be considered as SNR loss relative to normal hearing controls. The box-plots in Fig. 4 show the distribution for the NH and HI groups. Examination of histograms and Q-Q plots indicated that the measures were approximately normally distributed.

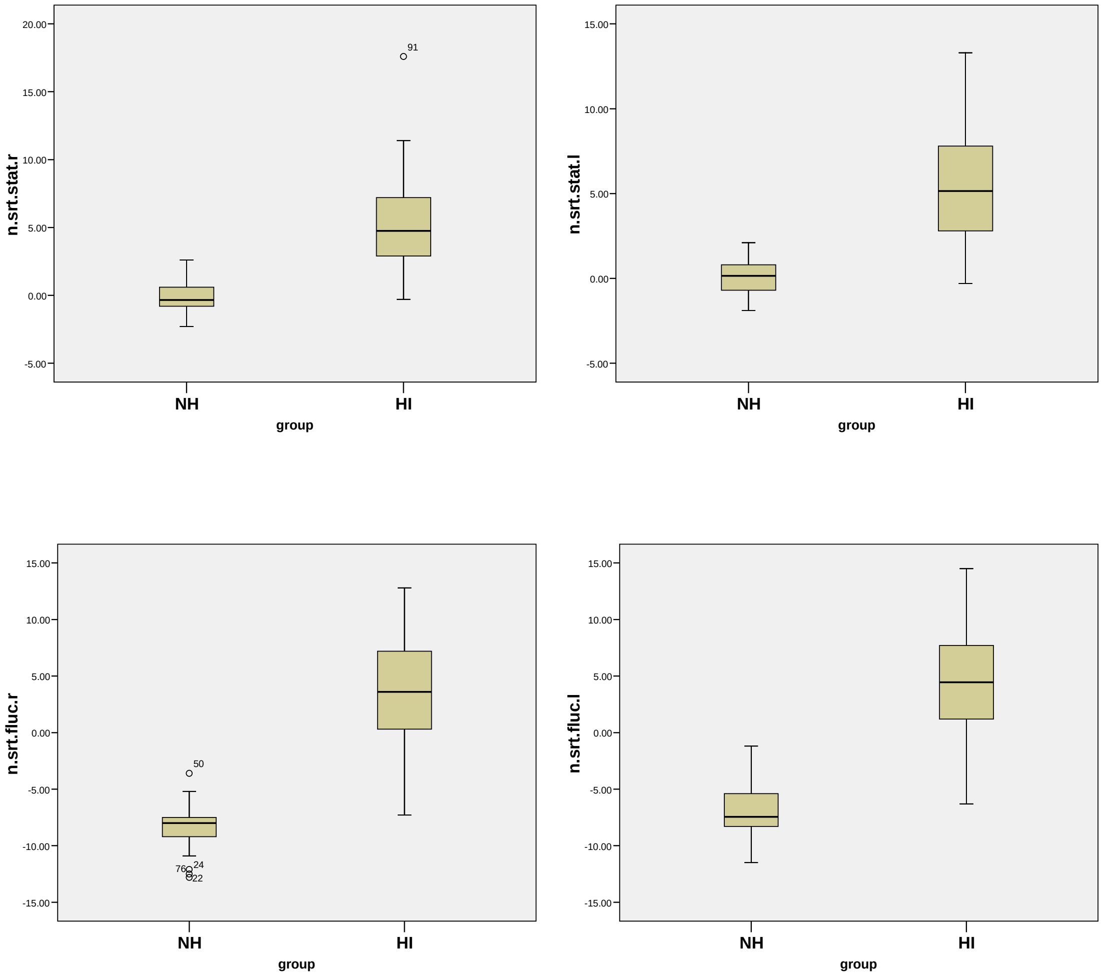

Figure 4: Measures of speech recognition in stationary (stat) and fluctuating (fluc) noise for right ear (left panel) and left ear (right panel) for normal-hearing and hearing-impaired listeners. The prefix “n” indicates that the values have been referenced to the average for stationary noise in normal hearing participants at the corresponding centre.

3.2.2 Distributions of binaural measures

3.2.2.1 Measures of spatial hearing

Spatial hearing was measured in terms of masking release for speech recognition in noise. The measure of speech recognition was in the matrix test format, according to the language of each centre. The noise was stationary noise with a frequency spectrum similar to the speech materials. Each test run entailed obtaining the SRT for 50% correct word recognition on the matrix test. Spatial hearing was invoked using virtual auditory space techniques that utilised standard head-related transfer functions (HRTF) and presentation via earphones. Speech was always presented using a HRTF for zero degrees azimuth and the reference condition entailed noise presentation for zero degree azimuth also.

Intelligibility level differences (ILD) were obtained from the differences between the reference condition and the test conditions with noise convolved with the HRTF for azimuths of +/-90 degrees. This measure of masking release includes the benefit of better SNR at the ear opposite the noise, plus the further dichotic advantage (“binaural squelch”) derived from utilising information at the ear with worse SNR.

A value for binaural squelch in isolation was obtained by also measuring in test conditions where the speech and noise for the earphone on the noise side were removed. By subtracting the SNR in this condition from the ILD test condition, a measure of binaural squelch was obtained.

As both the ILD and binaural squelch measures were calculated as differences, there was no need to adjust for language differences in the speech tests.

The box-plots in Fig. 6 show the distribution for the NH and HI groups. Examination of histograms and Q-Q plots indicated that the measures were approximately normally distributed.

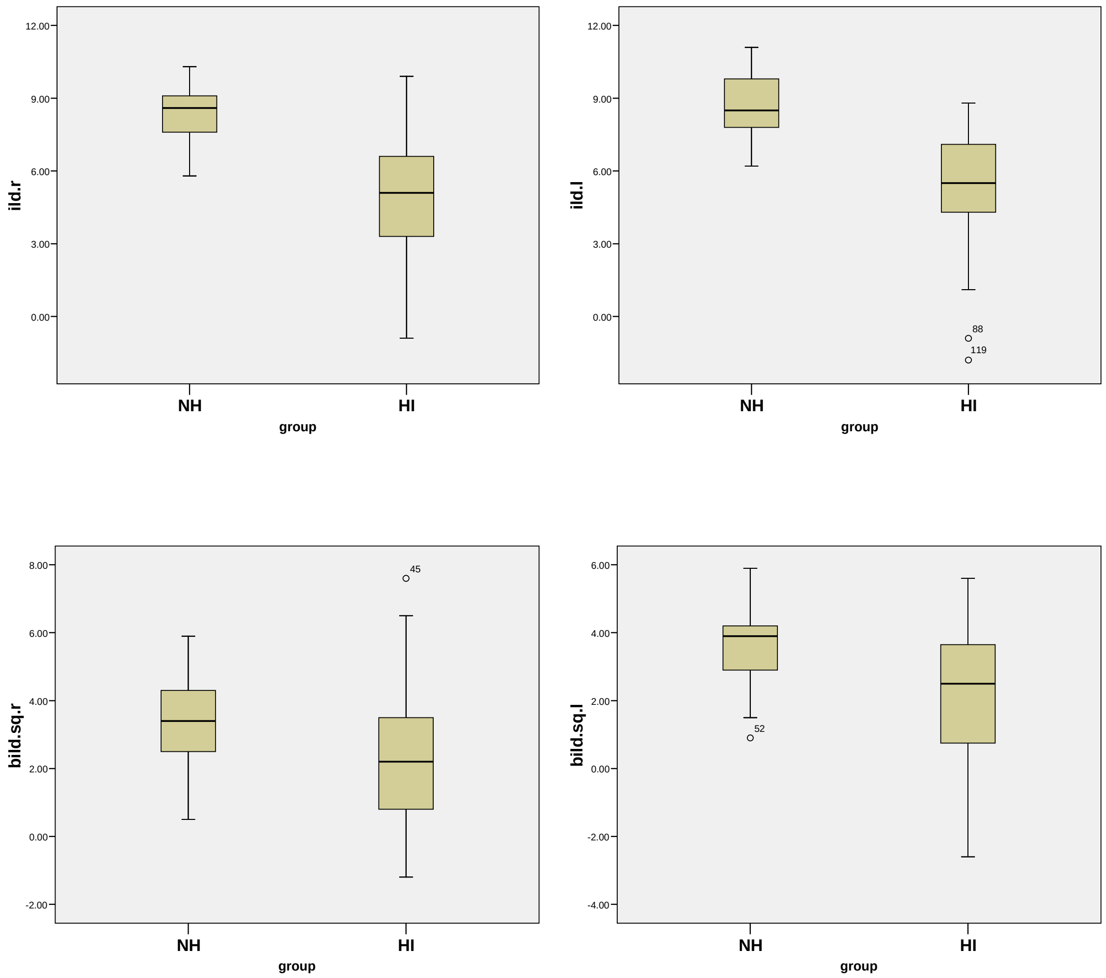

Figure 5: Measures of binaural speech recognition in noise (see text for explanation) for noise from the right ear (left panel) and left ear (right panel) for normal-hearing and hearing-impaired listeners.

3.2.2.2 Lexical processing

The lexical decision test gave measures of accuracy (score) and speed of processing (reaction time). There were two runs of the test, yielding two replicates of score and reaction time that were averaged to give a single measure of each. The box-plots in Fig. 6 show the distributions for the NH and HI groups. Examination of histograms and Q-Q plots indicated that the score was not normally distributed, which is the expectation for a percentage measure. Therefore the percent score was arcsine transformed for further analysis, which gave an approximately normal distribution. The reaction time measure was approximately normally distributed, with a few outliers at long reaction times.

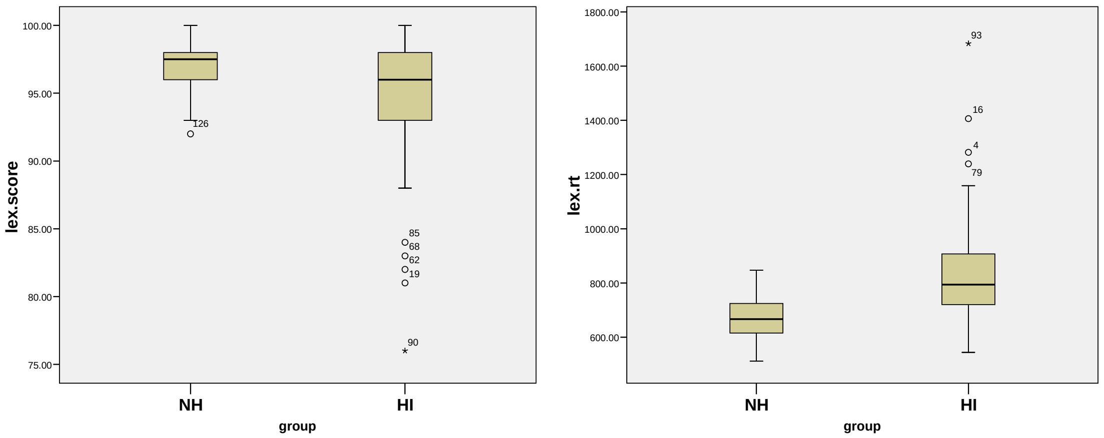

Figure 6: Measures of lexical processing for normal-hearing and hearing-impaired listeners. The suffix “rt” indicates reaction time.

3.2.2.3 Self-reported hearing difficulty

The four subscales of the Gothenburg Profile describe difficulties hearing speech (Speech), sound localisation (Localisation), relation to others (Relation) and performance and reaction to others (Perform). As these are all percentage scales, they were arcsine transformed for analysis to normalise the distributions. The box-plots in Fig. 7 show the distributions of the transformed scores for the NH and HI groups. Examination of histograms and Q-Q plots indicated that they were approximately normally distributed.

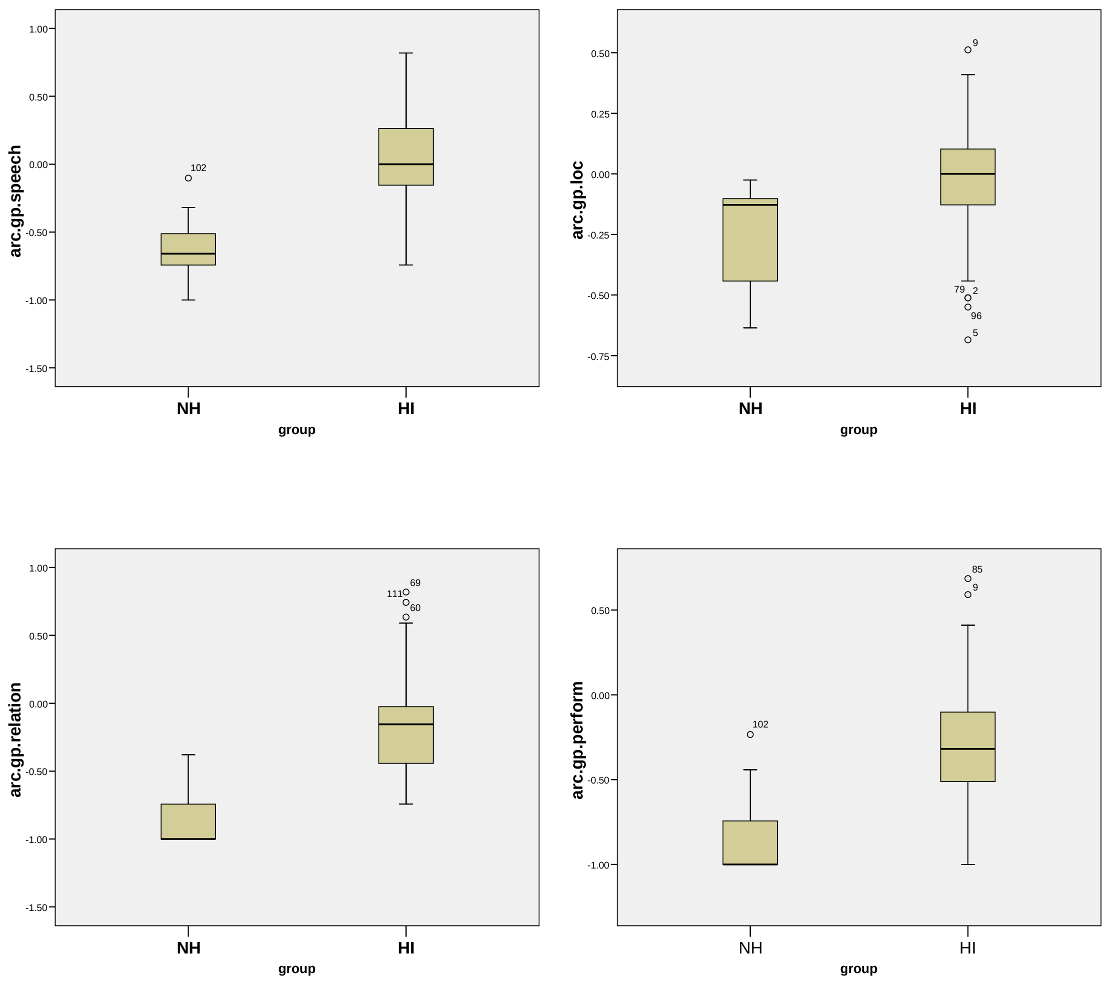

Figure 7: Measures of self-reported hearing difficulty from the Gothenburg Profile (see text for explanation of subscales) for normal-hearing and hearing-impaired listeners. The prefix “arc” indicates the results have been arcsine transformed.

3.3 Factor analysis

The aim of factor analysis is to seek underlying structures that describe the data more simply, reducing a large number of variables to a smaller number of factors. Factor analysis is based on the correlation matrix relating a number of variables. It is relevant here because the concept underlying the Auditory Profile is that hearing impaired people vary in ways that are multidimensional and cannot be explained simply in terms of conventional audiological measures (audiogram). If all the measures included in the present study were highly correlated, factor analysis would give a solution with only one factor. The following analyses used the principal component method with *varimax* rotation and included all participants. Rotation does not affect the proportion of variance explained by the factors but rotates the solution to aid interpretation.

3.3.1 Factor analysis for monaural measures

The first factor analyses included variables related to each ear separately: hearing threshold levels, frequency and temporal resolution, speech recognition in noise. Initially, two analyses were carried out, for the left and right ears and including all participants. Tables 3 and 4 show the rotated factor solutions. Factor loadings of 0.5 and above are highlighted in the tables.

Table 3. Rotated component matrix for monaural measures (right ear)

	Component		
	1	2	3
ra500	.352	.846	.069
ra1k	.470	.751	.115
ra2k	.804	.423	.123
ra3k	.914	.264	.157
ra4k	.914	.213	.165
SpecR500	.106	.793	.100
TempR500	.207	.750	.139
SpecR3k	.823	.212	.044
TempR3k	.643	.260	.098
lcut.r500	.033	.000	.881
mlo.r500	.192	.741	-.472
lcut.r3k	.207	.176	.823
mlo.r3k	.807	-.008	-.287
n.srt.stat.r	.787	.192	.108
n.srt.fluc.r	.762	.456	.091

The solutions for both right and left ears are very similar. The first factor can be interpreted as high-frequency sensitivity and resolution. It includes compression at high frequencies. It also includes the speech recognition in noise variables, suggestion that they are explained predominantly by processing of high-frequency information. The second factor can be interpreted as low-mid-frequency sensitivity and resolution. It includes low-frequency compression. The third factor can be interpreted as loudness tolerance and has very little correlation with the other two factors.

Table 4. Rotated component matrix for monaural measures (left ear)

	Component		
	1	2	3
la500	.318	.865	.023
la1k	.492	.745	.087
la2k	.809	.422	.158
la3k	.900	.300	.146
la4k	.910	.220	.183
SpecL500	.135	.776	.080
TempL500	.146	.692	.233
SpecL3k	.857	.139	.057
TempL3k	.721	.141	.114
lcut.l500	.046	.094	.902
mlo.l500	.224	.719	-.522
lcut.l3k	.414	.161	.746
mlo.l3k	.743	.236	-.259
n.srt.stat.l	.823	.131	.132
n.srt.fluc.l	.799	.379	.112

3.3.2 Factor analysis for binaural measures

The next factor analysis focused on overall auditory performance, rather than each ear separately. For this purpose, the hearing threshold levels, resolution measures, loudness and speech recognition measures used in the previous analysis were assigned to the better or worse hearing ear. For this purpose, the better hearing ear was defined according to the hearing threshold levels averaged across the frequencies 0.5, 1, 2 and 4 kHz. Only the better ear measures were included in the analysis (variables with prefix “b”). The binaural masking release measures (ILD and squelch) were averaged across noise azimuths (+/- 90 degrees), giving variables with suffix “rl”. The lexical decision test and transformed Gothenburg Profile subscale scores were also included.

The rotated factors are shown in Table 5. The two first factors can again be interpreted as high-frequency sensitivity and resolution and low-mid-frequency sensitivity and resolution. The first factor associates with the Speech subscale of the Gothenburg Profile. The second factor is not associated with any of the subscales of the Gothenburg profile. The third factor relates to the subscales of the Gothenburg Profile but not to any other measure, presumably reflecting subjective reaction to hearing impairment. The fourth factor can again be interpreted as loudness tolerance; it does not associate with any other measures. The fifth factor is interpreted as lexical processing and has little correlation with any other measures.

Table 5. Rotated component matrix for binaural measures

	Component				
	1	2	3	4	5
arc.gp.speech	.505	.386	.599	.157	.012
arc.gp.loc	.116	.481	.450	.045	-.216
arc.gp.relation	.427	.352	.747	.023	.079
arc.gp.perform	.353	.242	.800	-.017	.192
ba500	.255	.830	.224	.141	.022
ba1k	.367	.735	.274	.213	.005
ba2k	.728	.467	.256	.192	-.087
ba3k	.847	.306	.259	.178	.038
ba4k	.843	.236	.275	.212	.109
b.spec500	.193	.686	.170	-.065	.094
b.temp500	.112	.577	.332	.084	.235
b.spec3k	.797	.158	.220	.055	.055
b.temp3k	.646	.104	.228	.171	.019
b.srt.stat	.819	.068	.072	.040	.217
b.srt.fluc	.740	.405	.199	.127	.243
b.lcut.500	.072	-.006	.046	.879	.053
b.lcut.3k	.221	.157	.040	.832	.084
b.mlo.500	.146	.753	.103	-.444	-.007
b.mlo.3k	.808	.201	.027	-.216	.045
ild.rl	-.470	-.601	-.129	-.060	-.116
bild.sq.rl	-.115	-.717	-.018	-.112	-.093
lex.rt	.378	.166	-.104	-.047	.671
arc.lex.score	-.013	-.053	-.186	-.166	-.812

Further factor analysis including the absolute difference measures between better and worse ears did not yield an interpretable factor structure.

3.4 Regression analysis

Multiple linear regression analyses were performed using measures of speech recognition in noise as dependent variables. These analyses were carried out for left and right ears separately. Further analyses were performed using the Gothenburg Profile subscales as dependent variables, in this case with better ear measures and binaural measures as independent variables. One of the purposes of the regression analysis was to determine the extent to which the dependent variables could be predicted by conventional audiological measures, and how much prediction was improved by including other measures in the Auditory Profile.

The regression model involved stepwise inclusion of independent variables and a Gaussian error term. For every analysis, the distribution of residuals was checked for approximate normality, to justify the error model. Initial regression analyses included all participants.

3.4.1 Monaural speech recognition in noise

The two analyses with speech in stationary noise as dependent variables gave somewhat similar solutions, with hearing threshold level at 4 kHz as the main predictor variable, explaining 59% (right ear, Table 6) and 61% (left ear, Table 7) of the variance. For the right ear, in addition to hearing threshold level at 4 kHz, part of the variation in speech recognition was explained by high-frequency compression, low-frequency spectral resolution and hearing threshold level at 1 kHz. However, given the absence of these variables in the regression equation for the left ear, the generality of that finding is in doubt.

Table 6. Prediction of speech recognition in stationary noise (Right ear, NH and HI groups combined)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.743(a)	.552	.548	2.30637
2	.753(b)	.567	.560	2.27776
3	.763(c)	.583	.572	2.24483
4	.774(d)	.599	.585	2.21028

a Predictors: (Constant), ra4k
b Predictors: (Constant), ra4k, mlo.r3k
c Predictors: (Constant), ra4k, mlo.r3k, SpecR500
d Predictors: (Constant), ra4k, mlo.r3k, SpecR500, ra1k
e Dependent Variable: n.srt.stat.r

Table 7. Prediction of speech recognition in stationary noise (Left ear, NH and HI groups combined)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.785(a)	.616	.613	2.30794

a Predictors: (Constant), la4k
b Dependent Variable: n.srt.stat.l

The corresponding analyses with speech in fluctuating noise as dependent variables gave solutions explaining 72% (right ear, Table 8) and 68% (left ear, Table 9) of the variance. For both ears, hearing threshold level at 4 kHz and spectral resolution at 0.5 kHz contribute the vast majority of explained variance. The remaining variance is explained by low-frequency compression.

Table 8. Prediction of speech recognition in fluctuating noise (Right ear, NH and HI groups combined)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.790(a)	.625	.622	3.89084
2	.843(b)	.711	.706	3.43018
3	.853(c)	.728	.721	3.33996

a Predictors: (Constant), ra4k
b Predictors: (Constant), ra4k, SpecR500
c Predictors: (Constant), ra4k, SpecR500, mlo.r500
d Dependent Variable: n.srt.fluc.r

Table 9. Prediction of speech recognition in fluctuating noise (Left ear, NH and HI groups combined)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.792(a)	.628	.625	3.96161
2	.825(b)	.681	.676	3.68053
3	.832(c)	.692	.684	3.63570

a Predictors: (Constant), la4k
b Predictors: (Constant), la4k, SpecL500
c Predictors: (Constant), la4k, SpecL500, mlo.l500
d Dependent Variable: n.srt.fluc.l

The regression analyses above are influenced strongly by the distinctions between the NH and HI groups. Variation within the HI group is also of interest and the following analyses focus on just the HI group. For speech recognition in stationary noise, Tables 10 and 11 show that hearing threshold level at 4 kHz remains the most important predictive variable. For both ears, spectral resolution at 0.5 kHz is also a predictor. The percentages of explained variation are 35% and 50% for the right and left ears respectively. The regression analyses for speech recognition in fluctuating noise shown in Tables 12 and 13 below indicate that hearing threshold at 4 kHz and spectral resolution at 0.5 kHz remain the main predictors, explaining 34% (right ear) and 35% (left ear) of the variance.

Table 10. Prediction of speech recognition in stationary noise (Right ear, HI group only)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.542(a)	.294	.286	2.52566
2	.583(b)	.340	.326	2.45489
3	.610(c)	.372	.352	2.40688

a Predictors: (Constant), ra4k
b Predictors: (Constant), ra4k, SpecR500
c Predictors: (Constant), ra4k, SpecR500, mlo.r3k
d Dependent Variable: n.srt.stat.r

Table 11. Prediction of speech recognition in stationary noise (Left ear, HI group only)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.698(a)	.488	.482	2.39721
2	.714(b)	.510	.499	2.35705

a Predictors: (Constant), la4k
b Predictors: (Constant), la4k, SpecL500
c Dependent Variable: n.srt.stat.l

Table 12. Prediction of speech recognition in fluctuating noise (Right ear, HI group only)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.394(a)	.155	.146	3.98908
2	.593(b)	.352	.338	3.51267

a Predictors: (Constant), SpecR500
b Predictors: (Constant), SpecR500, ra4k
c Dependent Variable: n.srt.fluc.r

Table 13. Prediction of speech recognition in fluctuating noise (Left ear, HI group only)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.497(a)	.247	.240	4.21665
2	.599(b)	.358	.345	3.91396

a Predictors: (Constant), la4k
b Predictors: (Constant), la4k, SpecL500
c Dependent Variable: n.srt.fluc.l

3.4.2 Binaural speech recognition in noise

Further regression analysis focused on overall measures rather than separate left and right ears, for the combination of NH and HI groups. First, speech recognition in stationary noise obtained using the matrix tests and zero degrees noise azimuth was used as the dependent variable. Independent variables included the better-ear measures and also the absolute differences between better and worse ears. The latter variables were logarithmically transformed to obtain an approximately normal distribution. Age was also included as an independent variable. The regression model (Table 14) included better ear hearing thresholds at 4 and 0.5 kHz as well as the left-right difference in temporal resolution at 0.5 and 3 kHz. The latter variables added little to the explained variance and may not be a general finding. The first two variables explained 57% of the variance.

Table 14. Prediction of binaural speech recognition in noise (NH and HI groups combined)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.721(a)	.520	.516	1.7035
2	.759(b)	.576	.568	1.6092
3	.769(c)	.591	.580	1.5869
4	.777(d)	.604	.591	1.5668

a Predictors: (Constant), ba4k
b Predictors: (Constant), ba4k, ba500
c Predictors: (Constant), ba4k, ba500, lg.d.temp3k
d Predictors: (Constant), ba4k, ba500, lg.d.temp3k, lg.d.temp500
e Dependent Variable: ild.n0

3.4.3 Self-reported hearing difficulty

The next regression analysis involved the Gothenburg Profile subscales as dependent variables for the entire participant pool. For the Speech subscale, hearing threshold level at 2 kHz, temporal resolution at 0.5 kHz and threshold asymmetry at 1 kHz explained 59% of the variance (see Table 15 below). Subsequent iterations of the stepwise regression are somewhat unstable and do not add to the interpretation of the data. For the Localisation subscale (Table 16), hearing threshold at 1 kHz and ILD explained 29% of the variance. For the Relation subscale (Table 17), hearing threshold at 4 and 0.5 kHz explained 51% of the variance. For the Perform subscale (Table 18), hearing threshold at 3 kHz, temporal resolution at 0.5 kHz and binaural squelch explained 39% of the variance.

Table 15. Prediction of Gothenburg Profile Speech *subscale (NH and HI groups combined)*

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.688(a)	.473	.469	.27928
2	.738(b)	.545	.537	.26065
3	.772(c)	.596	.586	.24664
4	.782(d)	.612	.598	.24283
5	.792(e)	.627	.610	.23913
6	.802(f)	.643	.624	.23480
7	.798(g)	.637	.621	.23594

a Predictors: (Constant), ba2k
b Predictors: (Constant), ba2k, b.temp500
c Predictors: (Constant), ba2k, b.temp500, lg.da1k
d Predictors: (Constant), ba2k, b.temp500, lg.da1k, lg.d.temp3k
e Predictors: (Constant), ba2k, b.temp500, lg.da1k, lg.d.temp3k, ba4k
f Predictors: (Constant), ba2k, b.temp500, lg.da1k, lg.d.temp3k, ba4k, ba500
g Predictors: (Constant), b.temp500, lg.da1k, lg.d.temp3k, ba4k, ba500
h Dependent Variable: arc.gp.speech

Table 16. Prediction of Gothenburg Profile Localisation *subscale (NH and HI groups combined)*

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.514(a)	.264	.257	.19185
2	.548(b)	.300	.288	.18782

a Predictors: (Constant), ba1k
b Predictors: (Constant), ba1k, ild.rl
c Dependent Variable: arc.gp.loc

Table 17. Prediction of Gothenburg Profile Relation *subscale (NH and HI groups combined)*

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.652(a)	.426	.421	.32429
2	.686(b)	.471	.462	.31252
3	.702(c)	.493	.480	.30735
4	.727(d)	.529	.512	.29767
5	.725(e)	.526	.514	.29709
6	.722(f)	.521	.513	.29735

a Predictors: (Constant), ba2k
b Predictors: (Constant), ba2k, ild.rl
c Predictors: (Constant), ba2k, ild.rl, ba500
d Predictors: (Constant), ba2k, ild.rl, ba500, ba4k
e Predictors: (Constant), ild.rl, ba500, ba4k
f Predictors: (Constant), ba500, ba4k
g Dependent Variable: arc.gp.relation

Table 18. Prediction of Gothenburg Profile Perform *subscale (NH and HI groups combined)*

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.559(a)	.313	.307	.33313
2	.615(b)	.379	.368	.31821
3	.636(c)	.404	.388	.31300

a Predictors: (Constant), ba3k
b Predictors: (Constant), ba3k, b.temp500
c Predictors: (Constant), ba3k, b.temp500, bild.sq.rl
d Dependent Variable: arc.gp.perform

Restricting the regression analysis to the HI group reduced the explained variance substantially, especially for the Relation and Perform variables.

3.4.4 Predictions from audiogram and age

The next regression analyses examined the extent to which the speech recognition scores and self-report measures could be predicted from the conventional measures of the audiogram and age. For sentence recognition in steady noise, the conventional measures predicted 55% (right) and 62% (left) of the variance, compared to 59% (right) and 61%

(left) for the full set of measures. For sentence recognition in fluctuating noise, the explained variance increased from 69% (right) and 67% (left) to 72% (right) and 68% (left) for the full set of measures, due mainly to the addition of the measure of spectral resolution at 0.5 kHz. For the matrix test in noise (zero degree azimuth), there was a slight increase in explained variance from 57% to 59% by the addition of a measure of asymmetry of temporal resolution.

For the self-report measures, the explained variance for the Speech subscale increased from 56% to 62% by the addition of measures of temporal resolution. For the Localisation subscale, there was an increase from 27% to 29% due to the addition of a measure of ILD. For the Perform subscale, there was an increase from 34% to 39% due to the addition of a measure of temporal resolution at 0.5 kHz. There was no scope for improvement with the Relation subscale, as only audiometric variables were included from the full set of measures.

The final regression of this type analyses examined the extent to which the speech recognition and self-report measures could be predicted from age plus a single audiometric measure, the average of the hearing thresholds at 0.5, 1, 2 and 4 kHz. For the matrix test in noise, sentences in fluctuating noise and the self-report measures, the threshold average explained almost as much of the variance as the full set of psychoacoustic and audiometric measures (up to 6% less). However, for the sentence test in stationary noise, the full set of variables explained approximately 14% more of the variance.

In summary, the regression analyses showed that most of the variance in the speech recognition in noise test results can be explained from the audiogram. In fact, the combination of age and the simple average of thresholds at 0.5, 1, 2 and 4 kHz is a remarkably good predictor. The main exception to this latter rule is sentence recognition in stationary noise, where threshold at 4 kHz is a substantially better predictor than the 4-frequency average.

3.4.5 Prediction of speech recognition in spatial noise

Additional regression analysis examined the relationship between the measures of spatial hearing and other measures: better-ear hearing threshold levels, spectral/temporal resolution, loudness tolerance; asymmetry of hearing threshold levels, spectral/temporal resolution, compression and loudness tolerance. Table 19 shows that 55% of the variance in ILD was predicted by better-ear hearing threshold level at 4 and 0.5 kHz, spectral resolution at 0.5 kHz, asymmetry of hearing threshold level at 2 and 3 kHz, and asymmetry of compression at 0.5 kHz. For binaural squelch (Table 20), 35% of the variance was predicted by hearing threshold level at 0.5 kHz and asymmetry of hearing threshold level at 2 kHz. These analyses demonstrate the role of low-frequency hearing in the processing of spatial hearing cues.

Table 19. Prediction of ILD (NH and HI groups combined)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.578(a)	.334	.329	1.90380
2	.688(b)	.473	.464	1.70149
3	.712(c)	.506	.494	1.65316
4	.736(d)	.542	.526	1.59979
5	.746(e)	.557	.538	1.57970
6	.757(f)	.573	.550	1.55818

a Predictors: (Constant), ba4k
b Predictors: (Constant), ba4k, b.spec500
c Predictors: (Constant), ba4k, b.spec500, lg.da2k
d Predictors: (Constant), ba4k, b.spec500, lg.da2k, ba500
e Predictors: (Constant), ba4k, b.spec500, lg.da2k, ba500, lg.da3k
f Predictors: (Constant), ba4k, b.spec500, lg.da2k, ba500, lg.da3k, lg.d.mlo.500
g Dependent Variable: ild.rl

Table 20. Prediction of binaural squelch (NH and HI groups combined)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.573(a)	.329	.323	1.29729
2	.599(b)	.359	.348	1.27363

a Predictors: (Constant), ba500
b Predictors: (Constant), ba500, lg.da2k
c Dependent Variable: bild.sq.rl

4 Discussion

4.1 Notes on interpretation of the results

Discussion of the above results should properly start with a note of caution. The statistical methods used, factor analysis and multiple linear regression, are primarily descriptive and exploratory. They explore covariance in the available data set and are therefore dependent on idiosyncrasies present in the pool of participants who took part in the study. These limitations mean that caution is required when attempting to generalise from findings in the participant pool to the general population of people with hearing impairment. Using a large number of participants lessens this problem of generalisation. The present study was quite large by conventional standards in the field, with over 100 hearing impaired participants. Yet the number of measures included in some of the analyses was also large, which increases the problem of idiosyncrasy. For analyses that were performed separately for left and right ears, a degree of confidence can be assumed when both ears give the same pattern of results. However, for related reasons, differences in findings between the two ears must be treated with suspicion. In general, variables that explain substantial percentages of variance can be given greater weight than variables that explain only small incremental percentages of variance. The latter effects are prone to idiosyncrasy.

Another issue that requires caution in the interpretation of the results is co-variation between measures. In stepwise regression analysis where one of the independent variables is highly correlated with another, the regression model may include only one of the independent variables, because all significant correlation with the dependent variable is pre-empted by the first of the independent variables. The regression model could therefore exclude an independent variable that has intrinsic association with the dependent variable, while including another variable that does not have any intrinsic association. The latter is included indirectly through its correlation with the other independent variable and because by chance it has a slightly higher correlation with the dependent variable. Care must therefore be taken when interpreting the results of the regression analyses.

A further caution relates to the distinction between correlation and causation. This is particularly important when interpreting the role of hearing threshold levels in determining speech recognition performance in noise. The speech recognition tests within the Auditory Profile were all performed using presentation levels that were designed to make the speech materials audible to every participant. The presentation levels were increased for participants with poorer hearing thresholds. Therefore, performance on the tests should not have been limited by lack of audibility of the speech, at least for the parts of the frequency spectrum that are important for speech recognition. This is illustrated in the scatter plot in Fig. 7, which shows the presentation level for sentence recognition in stationary noise (right ear) as a function of hearing threshold level at 3 kHz. It can be seen that the speech level is greater than the 3-kHz threshold for all but the most impaired participants. When this information is combined with the knowledge that hearing threshold levels are the best predictors of speech recognition performance, it must be recognised that the prediction does not necessarily imply direct causation. Reduced performance may be correlated with poorer hearing threshold levels, but it does not necessarily occur through lack of audibility of speech components. Presumably, reduced performance on the speech recognition task occurs because of a variety of supra-threshold deficits (Plomp's D parameter) that happen to be predicted well by hearing threshold level.

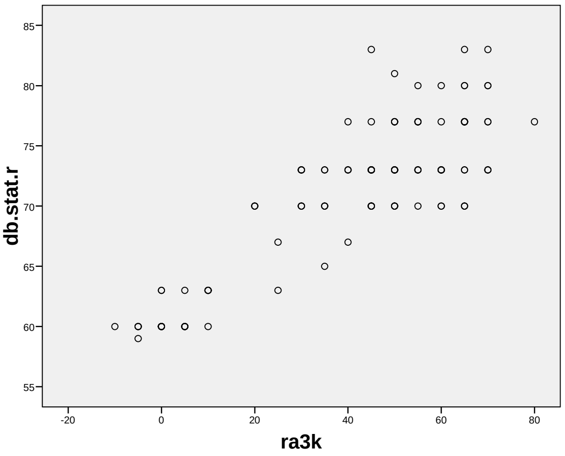

Figure 7: Relationship between speech presentation level and hearing threshold level at 3 kHz for normal-hearing and hearing-impaired listeners.

4.2 Comparison with initial Auditory Profile study

The results of the initial Auditory Profile study have been described in deliverable D-2-3. There were some differences in methodology that may affect the comparability of results, but they are not major differences. For example, the stimulus presentation levels for the initial study were based on measurement of MCL whereas in the present study they were based on a formula that estimates MCL. The initial study included replications to assess test-retest repeatability, whereas the present study included only a single replication for most measures. Moreover, the present study omitted measures of minimum audible angle and listening effort, based on analysis of the initial study (see D-2-3).

The factor analyses of right and left ear measures including both NH and HI groups were similar across studies. The main factors can be interpreted as high-frequency sensitivity, resolution and compression, low-mid-frequency sensitivity and resolution, and loudness tolerance. The factor analyses including binaural measures are not comparable across studies, partly because the first study included measures of minimal audible angle and partly because the present study analysis included better-ear measures for the tests that were administered per ear.

The regression analyses with sentence recognition performance as the dependent variable gave broadly similar results across the two studies. The key predictors in both studies appear to be audiometric threshold at 3 kHz (study 1) or 4 kHz (study 2) and spectral resolution at 0.5 kHz.

4.3 Comparison with previously published studies

Scope for comparison among studies is restricted by major differences in test methods and participant recruitment. Therefore, comparisons must necessarily be in broad terms. Festen and Plomp (1982) based their study on psychoacoustic measures centred on 1 kHz in 22 participants with sensorineural hearing loss, showing in factor analysis that speech recognition in quiet was associated with audiometric thresholds (audibility) while speech in noise performance formed a factor with measures of spectral resolution. Their results were consistent with the notion that speech recognition in quiet depends mainly on audibility whereas speech recognition in noise depends mainly on supra-threshold resolution (D parameter in Plomp model), mainly spectra resolution. This was confirmed by Lutman (1987) in a subset of 91 participants with normal hearing or mild sensorineural hearing loss, where spectral and temporal resolution at 4 kHz were the principal predictors of word recognition in noise scores. When the analysis included a further 48 participants with moderate sensorineural hearing loss, the principal predictors changed to hearing threshold level at 2 kHz and temporal resolution at 4 kHz. Divenyi and Haupt (1997) obtained a wide variety of measures of speech recognition in challenging listening conditions in 45 participants aged 60-81 years with mainly mild hearing loss and a reference group of 16 participants aged 18-26 years with normal hearing. They also obtained measures of auditory sensitivity and resolution. Factor analysis indicated that the two largest factors were audibility of the speech signal and speech understanding in noise. Interestingly, the measures of spectral (around 1 kHz) and temporal resolution (gap detection in wideband noise) were unrelated to hearing thresholds or speech recognition. Van Rooij and Plomp (1990) tested 72 participants aged 60-93 years using a wide range of auditory tests, including spectral and temporal resolution, cognitive tests and measures of speech recognition in quiet and noise. Factor analysis indicated two major components, the larger component representing high frequency hearing loss with age and the smaller component representing cognitive decline. The measures of spectral and temporal resolution (both centred on 0.8 and 2.4 kHz) did not relate to speech recognition performance. More recently, George et al. (2006)

focused on the release of masking of speech that occurs when noise is modulated. It is well known that there is a pronounced release of masking in listeners with normal hearing but this reduces with hearing impairment. George et al. (2006) tested 29 participants with sensorineural hearing loss and 8 with normal hearing, showing that the release of masking is associated with temporal resolution around 1 kHz and age.

Given the range of outcomes from the previous studies mentioned above, it is not surprising that those results of the present study that can be compared fit within that range. There is agreement among the studies that speech recognition in noise can be predicted fairly well be hearing threshold levels, particularly at 2-4 kHz. The studies differ when considering whether the prediction can be improved by considering alternative measures such as frequency and temporal resolution. Regarding speech recognition in fluctuating noise, it appears that different capabilities contribute to performance compared to stationary noise. However, there is disagreement over what those capabilities may be: the present study suggests frequency resolution at 0.5 kHz whereas George et al. (2006) suggest temporal resolution at 1 kHz.

4.4 Interpretation of findings

The main finding of the present study is that much of the explained variance in performance across the range from normal hearing to moderate-severe hearing impairment is related to hearing sensitivity at high frequencies, as expressed by the audiogram. Speech recognition performance is predicted almost as well by the audiogram as by a wider range of psychoacoustic and audiometric measures. In fact, the average of the hearing threshold levels at 0.5, 1, 2 and 4 kHz is almost as good. These findings are generally consistent across both the HearCom studies and with much of the previous literature. One reason why high frequency thresholds predict speech recognition performance may be simply the influence of audibility of important speech cues at high frequencies, which are needed to correctly recognise speech in the presence of masking noise. However, the speech test materials for the present study were presented at an estimate of the MCL, set independently for each participant, which would tend to ensure that speech was at a sufficient level to be audible. There may have been some cases with sloping hearing loss where high frequency speech cues were not audible, but not many, as indicated in the figure above.

It might be expected that auditory resolution would be more important than auditory sensitivity at the presentation levels used and it had been anticipated that measures of spectral and temporal resolution would have emerged from the regression models as more important than hearing thresholds. However, both spectral and temporal resolution are correlated with hearing thresholds, especially for hearing threshold levels above approximately 30 dB (Lutman et al., 1989). Therefore, an intrinsic effect of spectral or temporal resolution on speech recognition in noise may show up as a correlation with hearing threshold level, through their mutual correlation. Moreover, the aspects of spectral or temporal resolution that are measured by our tests may not be the same as the aspects that are important for speech recognition. It is possible that the important aspects are more strongly correlated with hearing thresholds than with the measures we have used.

The way we presented stimuli at different levels according to hearing loss may account for the lack of apparent importance of measures such as spectral resolution at 3 kHz. Spectral resolution measures depend on stimulus level, reflecting the nonlinear response of the basilar membrane. Because we have selected presentation levels according to individual hearing thresholds, spectral resolution measures may have become highly correlated with hearing threshold level, they may not have much further independent explanatory power. To a lesser extent, the same argument may apply to temporal resolution.

The regression analyses showed that the psychoacoustic measures explain in the region of 60% of the variance in the speech recognition measures, which leaves approximately 40% unexplained. Partly the latter will arise from measurement uncertainty, but we did not include replications that would allow an estimation of the contribution to unexplained variance of measurement uncertainty. However, an over-estimation of measurement uncertainty can be obtained by treating right and left ear measures as replicates, given the generally symmetrical hearing of the participants. Correlations between left and right ear measures were generally higher than the multiple correlations in the regression analyses, suggesting that the unexplained variance is only partially attributable to measurement uncertainty. There appears to be further systematic variance unexplained.

While our study does not throw much new light on the conundrum of what capabilities underlie speech recognition in noise, it is consistent with the general thrust of the published literature. Despite our attempts to limit the influence of audibility and the inclusion of measures of auditory resolution at both low and high frequencies, we have been unable to demonstrate strong effects of spectral and temporal resolution on speech recognition performance, particularly in stationary noise.

One measure that has been included in few previous studies is speech recognition in modulated noise, which may better reflect everyday listening than in stationary noise. We found a clear effect of spectral resolution at 0.5 kHz for speech recognition in fluctuating noise; this was less clearly present for stationary noise (shown on right but left ear data). This finding differs from that of George et al. (2006), who showed that temporal resolution was important instead, although his resolution measures were restricted to 1 kHz. The presence of spectral resolution at

0.5 kHz in our regression model is a robust finding, but the reason for this is not obvious.

The present study extended existing knowledge by also addressing issues of binaural hearing. The diotic measure of binaural speech recognition in noise was predicted predominantly by hearing thresholds as 0.5 and 4 kHz, which is not much different from the monaural analyses. In the dichotic condition with the noise spatially separated from the speech, there was an additional influence of spectral resolution at 0.5 kHz plus measures of hearing asymmetry. The masking release due to the presence of speech and noise on the adverse listening side (binaural squelch) was explained by hearing threshold at 0.5 kHz and a measure of threshold asymmetry. Taken together, these results emphasise the importance of low frequency hearing, including low frequency spectral resolution, on binaural speech recognition in noise. The other (rather obvious) finding is that binaural performance decreases with increasing ear asymmetry.

The present study also extended existing knowledge by examining predictors of self-reported hearing abilities. Interestingly, temporal resolution at 0.5 kHz helped to explain the Speech subscale scores of the Gothenburg Profile, whereas it was spectral resolution at 0.5 kHz that was included in the speech recognition performance tests, as outlined above. Moreover, ear asymmetry was a predictor of the Speech subscale scores, suggesting that self-reported abilities are influenced by conditions where the speaker may be on the worse hearing side. The Localisation subscale scores were predicted by measures in inter-aural intelligibility difference (ILD), which is unsurprising and suggests that self-reported localisation ability may by influenced by ability to resolve spatially separate sounds. The Relation subscale (social interactions) was simply related to the audiogram. The Perform subscale (behaviour and reaction) had a large proportion of unexplained variance. Its association with hearing threshold at 3 kHz and temporal resolution is similar to the Speech subscale and probably represents an influence of speech-based activities governing reaction to hearing impairment.

4.5 Clinical implications

One motivation of the present study was to develop and evaluate a set of measures of hearing ability that would be useful clinically. The Auditory Profile was designed so that it could be completed during a single clinical session, albeit rather a long one. It would add to the conventional practice of simply measuring the audiogram and perhaps obtaining an indication of speech recognition performance. Conventionally, these would usually be supplemented by clinical interview to discuss the nature of hearing difficulties experienced by the patient, either with a formal questionnaire or informally. Basic demographics would also be available (e.g. age and sex). The Auditory Profile would be useful if it added information that would help to explain the difficulties experienced by the patients, either self-reported or based on performance measures.

The evidence from the present study, unfortunately, does not provide much support for the usefulness of the Auditory Profile in the above respect. Measures of hearing difficulty (speech recognition and self-report measures) in our sample of people with normal hearing or fairly symmetrical sensorineural hearing loss were predicted quite well by the audiogram and age. The additional measures in the Auditory Profile did not add greatly to prediction of the measures of hearing difficulty. The exception to this statement is the measure of spectral resolution at 0.5 kHz, which helped to predict speech recognition in noise, especially for fluctuating and spatially separated noise condition. The reason why spectral resolution at low frequency is important is unclear, but may relate to distinguishing vowel contrasts or semi-vowels that have cues at low frequencies.

The Auditory Profile would also be useful if it was able to classify patients into meaningful groups. It is possible that the Auditory Profile does not predict hearing difficulty in the entire participant pool, because opposing effects in different groups cancel out. Analysis of the data from the present study searched for any evident clustering of participants into different groups characterised by measures from the Auditory Profile. However, no meaningful clustering was found; all participants tended to be distributed randomly around the principal trends in the data.

The present validation is cross-sectional and focuses on the characterisation of people with hearing impairment. This is in the clinical domain of diagnosis, aiming to understand causes of communication difficulties. The validation does not address potential application of the Auditory Profile in the domain of rehabilitation, where the question of interest is any change in communication difficulty due to treatment. An example would be an improvement in speech recognition performance in noise with a particular signal-processing hearing aid. The Auditory Profile would be useful clinically if it could predict the change in performance and therefore help to select the most beneficial type of processing for an individual. A different type of validation study is required to answer that question and remains for future investigation.

4.6 What have we found out that is new?

The study largely confirms and supports previous studies in showing that speech recognition in noise can be predicted well from the audiogram (and age). Our studies have overcome substantial methodological weaknesses in previous studies. The key advances include: large samples of participants (231 including both studies), measurement of auditory capabilities at both low and high frequencies, measurements in both right and left ears independently, ensuring audibility of speech across a range of hearing impairment. Essentially, we sought to demonstrate that variance in speech recognition in noise performance could be explained by measures other than the audiogram: our methodology aimed to enable the non-audiometric variables to show their importance. The fact that they did not provides strong evidence for the opposite conclusion. Furthermore, the absence of importance of non-audiometric variables cannot so easily be attributed to methodological weakness.

A novel finding is the importance of spectral resolution at 0.5 kHz, which was not measured in many previous studies. This may reflect coding of vowel contrasts in the lower frequency range.

5 Conclusions

1. Speech recognition performance in noise can be predicted well from conventional audiometric measures: specifically the audiogram and age. The average of the thresholds at 0.5, 1, 2 and 4 kHz, which has been used in many other studies to summarise hearing impairment, is nearly as good a predictor as a linear combination of all the conventional thresholds.

2. Prediction of speech recognition performance in noise is improved by the addition of a measure of spectral resolution at 0.5 kHz, especially for speech in fluctuating noise and when speech and noise are spatially separated.

3. It follows that for clinical purposes there is little to be gained from more complex psychoacoustic characterisation of sensorineural hearing impairment, when the purpose is to predict or explain difficulty understanding speech in noise. A conventional audiogram and possible measurement of spectral resolution at 0.5 kHz is sufficient.

6 Dissemination and Exploitation

6.1 Dissemination

The dissemination of the tests needed for the assessment of the auditory profile among professionals will be part of HEARCOM eServices.

For the dissemination of the results of the Auditory Profile, the main target groups are:

1. Researchers, working in audiological research and in hearing aid industry. The use of the Auditory Profile by other research groups can be arranged relatively easily.
2. Professionals working in clinical Audiology, such as audiologists, ENT surgeons and hearing aid acousticians. For the health professionals, HEARCOM will deliver diagnostic tools and a well-standardized battery of tests that comprises the auditory profile.

Given the fact that all tests have been implemented on the same software platform (Oldenburg Measurements Applications, OMA), there is a large potential to market the complete set of HearCom tests to the target groups described above.

An application of the Auditory Profile in the clinics needs a CE-approval of the equipment and the software packages used. This is not an easy task, and it will at least take some time before the Auditory Profile is ready to be disseminated to clinics and hearing aid dispensers.

The aim of the auditory profile is that it should be used as a diagnostic tool in a broad population of subjects with complaints about their performance in (auditory) communication tasks. However, the diagnostic scope here is not primarily on the medical impairment, but on auditory disability that impacts auditory functioning in daily life. In the future, the auditory profile should serve as a standard approach in a (specialised) hearing centre or clinic.

6.2 Ethical issues

The multi-centre study described in this deliverable has been approved by the medical ethical committee of all participating centres:

- AMC-NL: MEC 05/127 # 05.17.0934, dated August 3rd 2005
- HZO-DE: "Klinische Tests zur Bestimmung individueller Hördefizite und Kommuniationsfähigkeiten", dated November 15th 2006
- ISVR-UK: 791, dated February 13th 2007

- LINK-SE: M83-06
- VUMC-NL: MEC05/12 - 2006/171, dated November 2nd 2006

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