METHODS OF THE BEAR TEST BATTERY

Overview of the Test Battery

The proposed tests are divided into 6 categories: audibility, middle-ear analysis, speech perception, binaural-processing abilities, loudness perception, and spectro-temporal resolution. A detailed characterization of hearing deficits can be complex and needs to be simplified to efficiently investigate the specific compensation needs of the individual listener. The considered tests have shown potential for auditory profiling and their outcomes can be used for hearing-aid fitting. The list of tests is summarized in Table I.

Table I: List of the tests that form the BEAR test battery and their corresponding dimension.

Test Name	Test Dimension
A. Pure-tone Audiometry: **B.** Fixed level Frequency threshold (eAUD-HF)	Audiometry and Audibility
C. Word recognition scores in quiet (WRS-4UFC): **D.** Hearing in noise test (HINT)	Speech perception tests
E. Maximum frequency for IPD detection (IPDfmax) **F.** Binaural Pitch (Bpitch) **G.** Extended binaural audiometry in noise (eAUD-B)	Binaural processing abilities
H. Adaptive categorical loudness scaling (ACALOS)	Loudness perception
I. Fast spectro-temporal modulation sensitivity (fSTM)	Spectro-temporal modulation
J. Extended audiometry in noise. Tone in noise test. (eAUD-N) **K.** Extended audiometry in noise. Spectral masking release condition (eAUD-S) **L.** Extended audiometry in noise. Temporal masking release condition (eAUD-T)	Spectro-temporal resolution

The proposed tests have been implemented in a comprehensive framework, as part of this of the BEAR project (bear-hearing.dk). The optimal conditions for the new suggested tests (fast spectro-temporal modulation detection and extended audiometry) were evaluated in a limited number of subjects and decisions regarding the procedure and presentation level was taken. The following sections summarize the methods for each of the above tests.

Test procedure

The tests were conducted by three examiners with a background in audiology and hearing research. An interface containing all the tests was implemented in MATLAB. The MATLAB GUI enabled each examiner to perform a demonstration and a short training before each listening test, so the listener can get familiar with the procedure before starting measurements. For monaural conditions, the right ear was tested first in all listeners. If the standard deviation was higher than the one defined for each test or the listener was not able to perform the procedure, the examiner was able to administer an additional measurement. The tests consisting of threshold estimation using the AFC framework (Ewert, 2013) were repeated at least two times and the mean of the three measurements was considered as the final value. A repetition was considered as an outlier if it was greater than three scaled median absolute deviations. The time needed to complete the entire test battery did not take longer than 3 hours, distributed over two sessions, for any of the participants.

Test Protocol

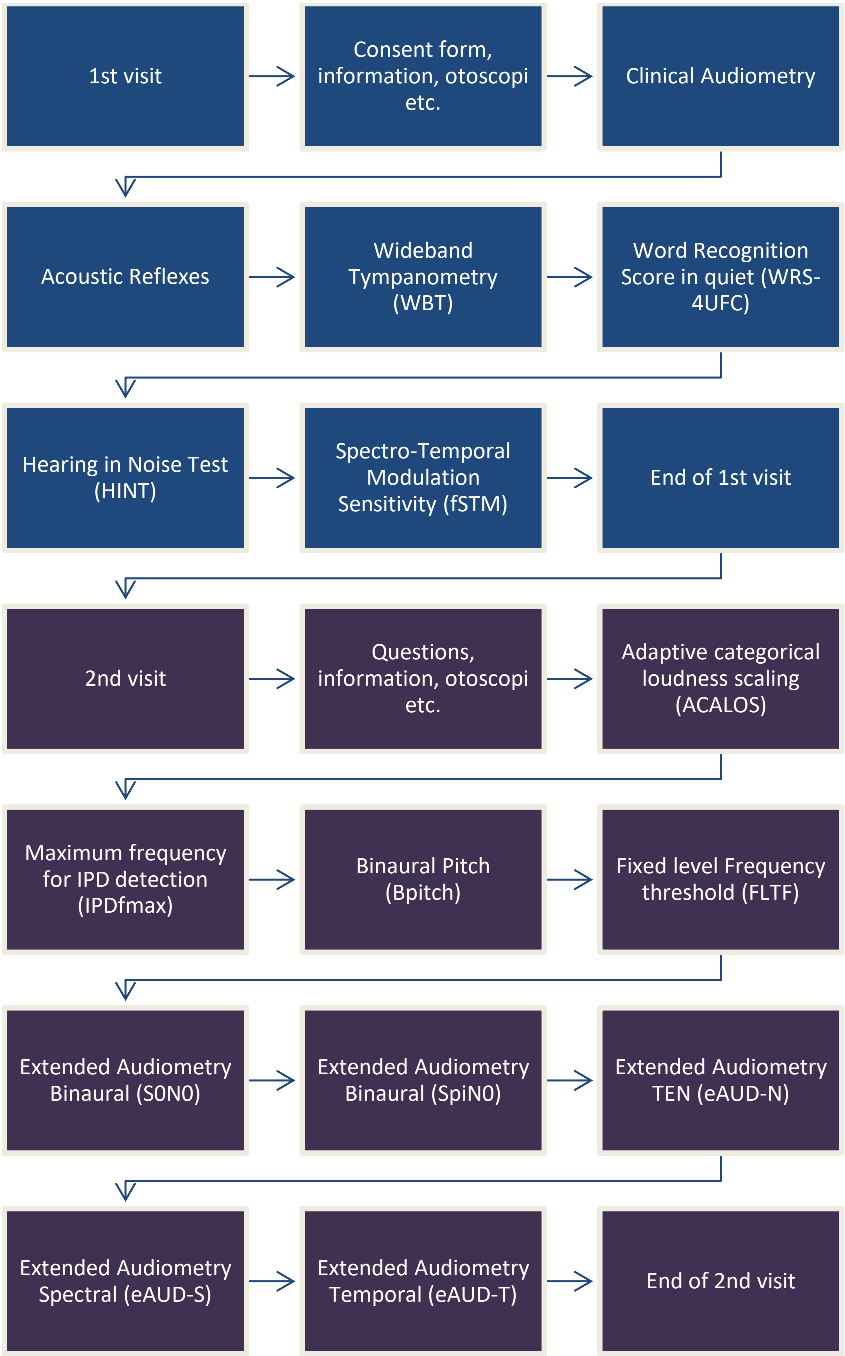

Figure 1: Diagram of the order of the tests in the two visits.

The same order was kept for the 1st and 2nd visits and for all the listeners as depicted in Figure 1. If some measurements could not be completed during a visit, they would be measured in a later visit. Systematical training was only used for the IPDfmax test. Instructions with a little training was done systematically for fSTM, Bpitch and FLTF test. Each measurement, except binaural tests, were first measured on the right ear unless the participant said that left ear is the better ear.

Pure tone Audiometry:

The pure-tone audiometry is still the “golden standard” in audiology, not only for fitting hearing aids but also for diagnostics. Overall, no alternative measure has provided enough evidence that could support the substitution or modification of this test. In the BEAR project, the standard (ISO 8253-1, 2010) was followed. However, it seems that the average at low and high frequencies or even the slope of the audiometric curve can provide more consistent information for classification purposes (Moore, 2016; Vlaming et al., 2011). The time estimation for a complete pure-tone audiometry is ~20 minutes.

Condition	Frequencies (kHz)	Ears	Outcome measures	Duration
Air-condution	0.125, 0.25, 0.5, 1, 2, 4, 8 Optional: 0.75, 1,5, 3 and 6	Left and Right	AUD_AVG AUD_LF AUD_HF	8-12 min
Bone-conduction	0.25, 0.5, 1, 2, 4	Left and Right	Air-Bone GAP	6-10 min

Speech perception tests

1. Word recognition scores in quiet (WRS-4UFC):

Word recognition in quiet is part of the tests used in speech audiometry, which is also a standardized procedure (ISO 8253-3, 2012) and the speech materials needed to perform the tests have been validated in several languages. Moreover, it is known that speech audiometry is useful for differential diagnostics, particularly in the case of sensorineural hearing loss (Dirks et al. 1977). While retro-cochlear hearing losses are often associated with speech functions with a characteristic roll-over, cochlear hearing losses with recruitment typically show maximum discrimination below 80% (Figure 2). However, the outcome of this test is not currently used in hearing-aid fitting rationales.

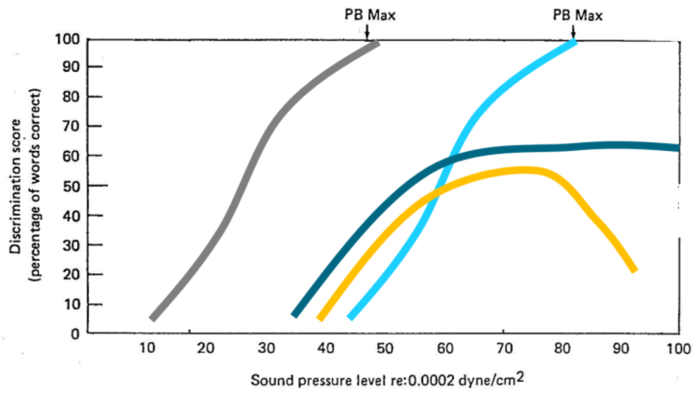

Figure 2: Speech audiometry profiles (adapted from Gelfand (2009)**.**

Word recognition scores are typically obtained by presenting a list of 25 monosyllabic phonetically balanced words at different levels above the pure-tone audiometric threshold. In the BEAR test battery, a 4-unforced-choice paradigm has been introduced. After the word is presented, four alternatives were shown on the screen, as well as a question mark. The four words have been carefully chosen previously. The target is placed randomly in one of the four buttons, together with the 3 words with the lowest Levenshtein distance (Sanders & Chin, 2009) that are also part of the Dantale I corpus.

Parameter	Values	Comments
Procedure	Constant stimuli	
Conditions	PTA + 40, 30, 20, and 10 dB PTA: pure-tone audiometric thresholds average (0,5 – 2 kHz)	The PTA is calculated by the software.
Ears	Left and Right	
Corpus	Dantale I	
Lists	25 monosyllabic words	
Duration	12 minutes (both ears)	This includes the explanation of the task.
Outcome measure	WRS_maxDS SRTQ WRS_ROIndex	Maximum discrimination score Speech reception threshold Roll-over index

2. Hearing in noise test (HINT)

The Hearing in noise test (HINT, Nilsson, Soli, & Sullivan, 1994) was first introduced by Plomp & colleagues as an adaptative sentence recognition test in long-term speech averaged spectrum noise. Furthermore, Plomp (1978) defined the distortion component (D), which appears when SRT is elevated even if the audibility is compensated for by amplification under the HINT conditions. In the BEAR test battery, Danish HINT was used as in (Nielsen & Dau, 2011). Additionally, a list presented at a fixed signal-to-noise ratio of 4 dB SNR was scored for the entire 20-sentences list and presented as a sentence recognition score. The outcome measures of this test were the speech reception threshold and the sentence recognition score at 4 dB SNR.

Parameter	Values	Comments
Procedure	1up-1down fixed SNR	
Conditions	SRT (50%) in speech Fixed 4 dB SNR	
Noise type	Speech-shape stationary noise (HINT noise)	
Ears	Left and Right	
Corpus	HINT (CLUE)	
Lists	20 sentences	
Noise Level	PTA + 30 dB PTA: pure-tone audiometric thresholds average (0,5 – 2 kHz)	Adjusted manually by the examiner
Duration	12 minutes (both ears)	This includes the explanation of the task.
Outcome measure	HINT_SRT HINT_SC	Speech reception threshold in noise Score for a fixed +4 dB SNR

Binaural processing abilities

3. Maximum frequency for IPD detection (IPD$_{fmax}$)

Interaural phase difference (IPD) detection abilities have been connected to the sensitivity to temporal fine structure (Brian C J Moore, 2007). The Maximum frequency for IPD detection when the signal in both ears has an IPD = 180º for determining has been successfully measured in hearing-impaired listeners (Santurette & Dau, 2012; Neher et al. 2011) showing a reduced sensitivity in some of the cases that were not correlated to the loss of audibility. In the BEAR test battery, the stimulus duration and procedure are identical to the method proposed by Füllgrabe et al. (2017), as this procedure has been found reliable and without training effects in older listeners. However, the step-size considered here differs slightly by reducing the step size first in steps of 2/3-octaves, then 1/3 octave and finally half of a 1/3-octave. These modifications should not affect the results in terms of accuracy.

Parameter	Values	Comments
Procedure	1up-2down (~70% psychometric function) 2 AFC	
Conditions	Single condition in a binaural	
Stimuli	Pure-tone with inverted phase in the contralateral ear.	

Parameter	Values	Comments
Level	35 dB SL	
Presentation of the stimuli	Sequence ABAB. The subject is asked whether the 4 sounds are the same or not	
Tracking variable	Frequency in logarithmic scale	
Step size	Decreasing step-size 2/3, 1/3 and 1/6 octave	
Reversals	6	
Repetitions	2	
Time	7 minutes	Including training
Outcome measure	IPD_FMAX	Maximum frequency for detecting an interaural phase difference of 180°

4. Binaural Pitch

Binaural pitch is a test that was previously used in Santurette & Dau (2012) as a pitch contour detection and identification task. The task consists of the detection of a melody embedded in noise. Each run consists of a set of 10 diotic and 10 dichotic melodies allocated randomly along with a sound file of 2 minutes length. While the diotic melody can be detected monoaurally, the dichotic melody can be only perceived if the binaural processing abilities are intact. This is because the tones that form the melody are indeed generated by adding phase-difference patterns to the noise presented in the two ears, which creates a pitch percept (Cramer & Huggins, 1958). The listener is asked to press the button each time he or she can hear the pitch contour. Then, the noise starts and a *training* pitch contour is played diotically at a higher level. Subsequently, the diotic and dichotic melodies are presented. Finally, a score is obtained for the diotic and dichotic conditions. Figure 2 shows the user interface of the binaural pitch test.

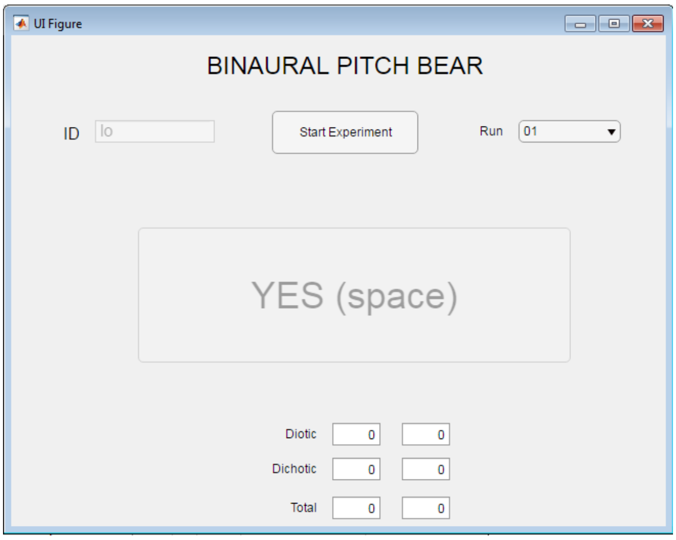

Figure 3: The user interface of the Binaural Pitch test.

Parameter	Values	Comments
Task	Pitch contour detection	
Stimuli	Diotic and Dichotic pitch contours embed in a noise	
Presentation Level	70 dB SPL	
Number of presentations	10 Diotic 10 Dichotic	
Repetitions	2	BP_20 refers to the two repetitions
Time	5 minutes	
Outcome measures	BP_20 BP_20_tot	Detection score of the dichotic stimuli Total detection score (Dichotic and Diotic)

Loudness perception

5. Adaptive categorical loudness scaling (ACALOS)

The assessment of loudness perception is a matter of interest to the audiology community. ACALOS is a standardized procedure (ISO 16832, 2006) for measuring loudness, which provides information about the growth of loudness and the most comfortable levels. In previous studies, its relations to auditory thresholds (Al-Salim et al. 2010), basilar membrane compression (Jürgens, Kollmeier, Brand, & Ewert, 2011) and fitting of dynamic compression in HAs (Oetting, Hohmann, Appell, Kollmeier, & Ewert, 2016) have been investigated.

The method consists of the categorical scaling of a 1/3-octave noise presented at a certain level. In each presentation, the listener is asked to give a category between *"not heard"* and "*extremely loud*". Shows the user interface where the categories are on a 11-point scale (see Figure 4). The presentation level of the next stimulus is calculated based on the previous trials (Brand & Hohmann, 2002). In the BEAR test battery, ACALOS was measured monoaurally in each ear. Figure 3 shows the user interface of ACALOS. The stimuli were presented at a certain SPL level. However, the raw data was transformed in dB hearing level according to the ISO 389-7. Once the raw data was in dB HL, the the model of loudness used in Brand & Hohmann, (2002) was fitted to the data providing the lower slope (m low), the Locut and the higher slope (m high). From the loudness funtion result of the model parameters, HTL was estimated as the first value above 0 CU, MCL as the the level value corresponding to 25 CU and the UCL as the level value corresponding to 50CU.

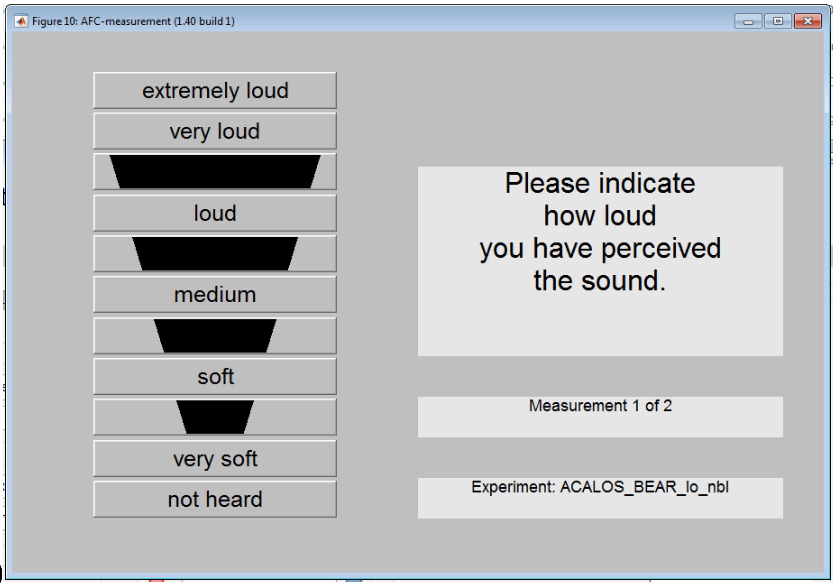

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Figure 4: User interface of the ACALOS test.

Parameter	Values	Comments
Procedure	ACALOS (Brand & Hohmann, 2002)	
Ears	Monoaurally, Left and Right	
Stimuli	1/3-octave noises centered at: 250 – 500 -1000 – 2000 – 4000 -6000 Hz	
Level	Adaptive level from -10 to 105 dB SPL	
Repetitions	1	
Time	20 minutes	
Outcome measure	HTL_AVG HTL_LF HTL_HF MCL_AVG MCL_LF MCL_HF UCL_LF UCL_HF DynR_L DynR_R Locut_LF Locut_HF Slope_AVG Slope_LF Slope_HF m_high_LF	HTL: Hearing thresholds estimation. (1 CU). MCL: Most Comfortable level (25 CU). UCL: Uncomfortable level (50 CU). DynR: Dynamic Range. Locut: ACALOS output parameter, the level where the linear parts intersect. Slope: m_low output parameter. The slope of the lower linear part. M_high: output parameter, the slope of the higher linear part. OHC: Outer hair cell loss estimation from the ACALOS results.

Parameter	Values	Comments
	m_high_HF OHC_LF OHC_HF	

Extended Audiometry

6. Fixed-level Frequency threshold (eAUD-HF)

The fixed-level frequency threshold (FLFT) provides an estimate of the maximum audible frequency and it has been proposed as a quick and efficient alternative to the high-frequency audiometry (Rieke et al., 2017). Recently, elevated thresholds at frequencies above the frequencies used in the standard pure-tone audiometry have been connected to the concept of “hidden hearing loss” and synaptopathy (Liberman, Epstein, Cleveland, Wang, & Maison, 2016). In the BEAR test battery, few modifications have been proposed compared to the method used in Rieke et al., (2017). The task consists of a tone detection presented at 80 dB SPL. In the current implementation, the target is a warble tone, which is particularly useful to avoid standing waves in the ear canal. Furthermore, the procedure used here is a yes/no task using a single-interval adjustment-matrix (SIAM) as described in Kaernbach (1990). In each trial, the target can be present or not. If the target is detected the frequency is increased according to the step-size; if it is not detected the frequency is decreased. However, if the stimulus is not presented (*catch trial*) but the listener provides a positive response, the frequency is decreased compared to the previous trial. Thus, the bias and criterion are controlled during the experiment which yields in a response pattern that is considered less arbitrary than the Békesy method.

Parameter	Values	Comments
Procedure	SIAM	
Conditions	Single condition	
Ears	Left and Right	
Stimuli	Warble tones in quiet	
Stimulus level	80 dB SPL	
Tracking variable	Frequency in logarithmic scale	
Starting frequency and range	Starting frequency: 8 kHz Range: 2 – 20 kHz	
Step size	1/2, 1/5 and 1/10 octave	
Reversals	2 discarded, 4 measurements	
Repetitions	2	
Duration	5 minutes	This includes the explanation of the task.
Outcome measure	FLFT	Fixed-level frequency threshold. Maximum detected frequency at 80 dB SPL

7. Extended audiometry in noise (eAUD)

The standard audiometry provides information about the sensitivity to pure tones. However, the perception of tones in background noise can be interesting for different purposes, such as assessing dead cochlear regions (B. C. J. Moore, 2001) or a combined measure of spectral and temporal resolution, the so-called F-T test (Larsby & Arlinger, 1998; van Esch & Dreschler, 2011).

The assessment of temporal and spectral resolution is based on the difference between the detection in noise and the detection when the temporal or spectral characteristics of the noise make the detection much easier and a release from masking is observed. The masked thresholds was performed with the level of the masker at 70 dB HL and it consists of 3 conditions as sketched in Figure 4:

eAUD-N (Noise): Threshold equalized noise (TEN).

eAUD-S (Spectral): Noise is off-frequency.

eAUD-T (Temporal): Noise is temporally modulated.

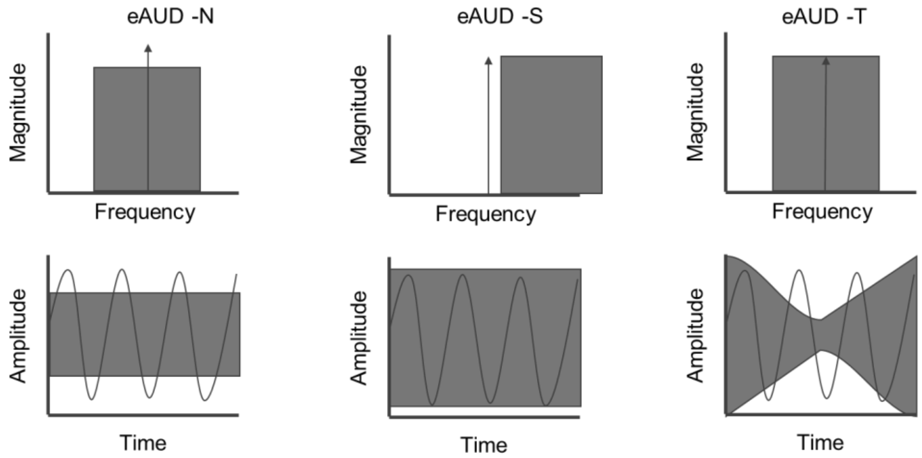

Figure 5: Sketch of the conditions of the extended audiometry (eAUD).

The eAUD-S, in combination with the TEN HL test (equivalent to eAUD-N), can provide an estimate of frequency selectivity. Noise is a 3-octave band TEN played at 70 dB HL in both cases. However, eAUD-S uses simultaneous masking but off-frequency, where the lower cut-off frequency in normalized frequency is 1.10 (Figure 5). Therefore, a masking release is expected if the auditory filters are sharply tuned (normal-hearing listeners). This release of masking can be related to the tip-to-tail distance presented in PTCs.

The eAUD-T, together with the eAUD-N, provides an estimate of the temporal resolution in line with the F-T test and the concept of a temporal resolution factor introduced by Zwicker & Schorn (1982). Here, the same 1/3-octave TEN noise is temporally modulated with a modulation frequency of 4 Hz (Figure 5). This *unmasks* the target and provides a masking release because of the listening in the dips advantage.

Parameter	Values	Comments
Procedure	SIAM	
Conditions	Noise Temporally modulated noise (fm=4Hz) Shifted noise (fl=1.3fc)	
Ears	Left and Right ear independently	
Stimuli	Tone in TEN noise	
Frequencies	500 and 2000 Hz	
Noise Level	70 dB HL	
Tracking variable	Level of the tone	
Step size	Decreasing step size 10, 5, 2 dB	
Reversals	2 discarded, 4 measurement	
Repetitions	2	
Outcome measures	EAUD_N_LF EAUD_TMR_LF EAUD_SMR_LF EAUD_N_HF EAUD_TMR_HF EAUD_SMR_HF	EAUD-N: Tone in noise in dB SPL TMR: Temporal masking release SMR: Spectral masking release
Time	25 minutes	

8. Extended binaural audiometry in noise (eAUD-B)

Masking level differences consist of two measurements; 1) the masked thresholds for detecting a pure tone in one-octave band noise presented diotically, 2) masked thresholds with the same noise but in antiphase in one of the ears (dichotic) (Brown & Musiek, 2013). As a result, a masking release of about 15 dB is expected in a healthy ear (Durlach, 1963). This measurement has been connected to Temporal fine structure (TFS) sensitivity (Strelcyk & Dau, 2009) and binaural pitch perception (Santurette & Dau, 2012) and it seems to be a promising test for characterizing the binaural performance.

Although new audiometer models have recently included masking level differences (MLD) following the procedure proposed in Brown & Musiek (2013), in the BEAR test battery, this test has been included as a part of the extended audiometry (eAUD).

The test is a simple tone detection task in threshold equalizing noise (TEN) in two conditions:

1) S_0N_0: Noise and tone have the same phase in both ears.

2) $S_{pi}N_{0}$: The tone is played in anti-phase in both ears.

The advantage of measuring MLD in similar conditions as the eAUD is that the binaural and 2 monoaural measures can be also compared.

Parameter	Values	Comments
Procedure	SIAM	
Conditions	Diotic condition (S0N0) Dichotic condition (SpiN0)	
Stimuli	Tone in TEN noise	
Frequencies	500	
Level	70 dB HL	
Tracking variable	Level of the tone	
Step size	Decreasing step size 10, 5, 2 dB	
Reversals	2 discarded, 4 measurement	
Repetitions	2	
Time	6-7 minutes	
Outcome measures	EAUD_BMR	Binaural masking level difference.

Spectro-temporal modulation sensitivity

9. Fast spectro-temporal modulation sensitivity (fSTM)

Speech signals are quite dynamic in that they exhibit spectral and temporal modulations. Recently, Bernstein et al., (2013) and (Mehraei, Gallun, Leek, & Bernstein, 2014) showed significant differences between normal-hearing and hearing-impaired listeners in spectro-temporal modulation (STM) detection sensitivity and its relation to speech intelligibility in noise. Furthermore, the reduced STM sensitivity in HI listeners has been ascribed to temporal fine structure processing deficits and a loss of frequency selectivity. Recently, (Bernstein et al., 2016)showed a large range of STM sensitivity across HI listeners. While some of them reached thresholds at similar values to the ones of NH, others were not able to perform the test. In the BEAR project, a fast spectro-temporal sensitivity test (fSTM) was suggested. A pilot study not shown here investigated different alternatives of a fSTM test, which provided promising results.

The fast STM sensitivity measurement consists of a YES/NO task in a constant stimuli procedure with catch trials. The stimulus presented is a sequence of 4 noises following an ABAB pattern. While A segments are unmodulated noises, B segments are spectro-temporally modulated. The catch trial consists of an ABAB sequence where the modulation is well below the threshold obtained in NH in previous studies.

Parameter	Values	Comments
Procedure	sSTM (screening based the score obtained on 10 presentations at -3 dB) SIAM	
Conditions	3-octave noise carrier centered at 800 Hz. fm=4Hz, Ω=2c/o 1-octave noise carrier at 4kHz fm=4Hz, Ω=4c/o	The low-frequency stimulus is similar to the one in Bernstein et al. (2016).
Stimuli	Sequence ABAB where A is unmodulated noise and B is modulated.	
Tracking variable	Modulation depth in logarithmic scale 20log(m)	
Steps	5, 2, and 1dB	
Reversals	2 discarded, 4 measurement	
Repetitions	2	
Outcome measures	Estimation of the 80% percent of the psychometric function (dB)	
Time	Screening test: 1.5 minutes Test: 10-15 min	
	sSTM_8 sSTM_4k fSTM_8 fSTM_4k	sSTM: screening STM test. Sensitivity (d') for – 3 dB condition fSTM: Spectro-temporal modulation detection threshold

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Appendix: Middle ear analysis

Acoustic Reflexes

Besides the psychoacoustic auditory tests, some of the subjects participated in an additional test. The acoustic reflex measurement is an objective test. It is easy to perform and provides information not only about the middle ear but also about later stages of the auditory pathway. Although the reflex affects the transmission of the middle ear, it is elicited by the medial olivocochlear system. In the case of a contralateral measurement, binaural processing is needed to elicit the reflex in the contralateral ear. Recently, the wideband middle ear muscle reflex has received much attention in connection to hidden hearing loss (Valero, Hancock, & Liberman, 2016). Therefore, it is considered here as an outcome measure that can be related to retro-cochlear processes (Stach, 1987).

In the BEAR test battery, the acoustic reflexes were measured both ipsi- and contra-laterally and elicited by wide-band noise. The threshold were obtained by repeated measures at different levels, starting at 60 dB SPL with a limit of 110 dB SPL. Furthermore, the latency of the reflex were also obtained at least 5 dB above the threshold. An Interacoustics Titan device were used to evaluate the middle ear function.

Parameter	Values	Comments
Device	Interacoustics TITAN	
Conditions	Ipsi-lateral Threshold Ipsi-lateral Latency Contra-lateral Threshold Contra-lateral Threshold	
Ears	Left and Right	
Stimuli	Broadband noise	
Initial and final Stimulus level	60 dB SPL – 110 dB SPL	
Tracking variable	TH: Threshold for acoustic reflex LT: No adaptive procedure	
Step size	2 dB	
Criterion	0.5 ml difference in compliance	
Repetitions	2	(If the two measures differ more than 5 dB take a third one)
Duration	5 minutes	This includes the explanation of the task.
Outcome measures	AR_TH_IP AR_TH_CN AR_LT_IP AR_LT_CN	TH: Threshold LT: Latency IP: Ipsilateral CN: Contralateral