Estimation of auditory filter shapes across frequencies using machine learning

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Introduction

When fitting a hearing aid, the level-dependent gain prescribed at each frequency is usually based on the hearing loss at that frequency. This often results in reasonable fittings for a typical cochlear hearing loss, but may fail when the individual frequency selectivity and/or loudness growth are different from what would be typical for that hearing loss. A popular measure of frequency selectivity is the notched-noise method, but this test is time-consuming.

To reduce testing time, Shen and Richards (2013) proposed an efficient machine-learning (ML) test that determines the slope of the skirts of the auditory filter (p), its minimum response for wide notches (r), and detection efficiency (K) for a given signal frequency (fs). We extended this approach with a test that yields notched-noise thresholds as a continuous function of fs for nine chosen notch widths. Any (low-parameter) auditory-filter model can be fit using these threshold data. We chose a model with three parameters, two parameters for the slope (lower slope, pl, and upper slope, pu) and K. Considering the asymmetry of the auditory filter while fitting a hearing aid can be useful to reduce across-channel masking.

Method

Subjects

6 hearing-impaired subjects (2 female, 4 male; 55-82 years, mean 68 years)

Stimuli

- Signal frequency (fs): 500 Hz to 4000 Hz or where HL becomes > 40 dB
- Signal level: 15 dB SL
- Noise width: 0.4 fs for each band
- Notch widths between fs and lower noise|upper noise: 0|0, 0.1|0.1, 0.2|0.2, 0.3|0.3, 0.4|0.4, 0.1|0.3, 0.3|0.1, 0.2|0.4 and 0.4|0.2 fs.
- Noise level (Lm): variable, maximum frequency dependent to avoid clipping
- Noise duration: 850 ms; signal: three 150-ms pulses, 100 ms between
- Monaural presentation with headphones (Sennheiser HDA200)

Procedure

- Three intervals: 1) Signal only, 2) Noise only, 3) Signal + noise
- Yes-no task: Did you hear the signal in the third interval?
- 540 trials + 54 catch trials without signal in the third interval (~ 60+6 per notch)
    - Breaks controlled by subject (possible after any trial)
    - Duration: 48-61 minutes
- Circa 11 trials per notch width on an adaptive initial grid
- Thereafter: Probabilistic modeling of thresholds with a Gaussian Process (GP)
    - Exploits smoothness of thresholds for adjacent fs and monotonicity of Lm
    - Gives a distribution for each pair of fs and Lm (50% mean shown in Fig. 1)
- For next trial: Choice of notch width, fs and Lm that yield maximum information

- Additional run: 60 trials for 0.2|0.2 notch (+6 catch trials)
- 2up/1down 2AFC, five notches (0, 0.2|0.2, 0.4|0.4, 0.2|0.4, 0.4|0.2) at 1400 Hz

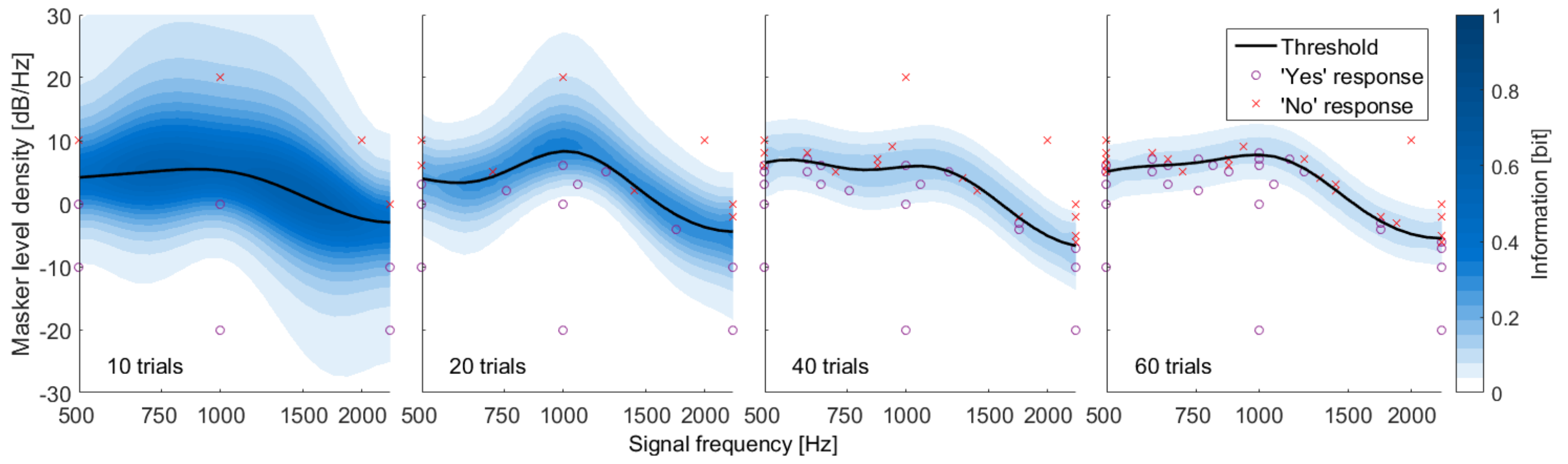

Fig. 1: Illustration of the machine-learning procedure for subject S2 and the 0.2|0.2 notch. The panels show the current estimate of the threshold (black line) and the information that can be obtained in the next trial as a function of fs and Lm after 10 trials (i.e. after the initial grid), 20, 40 and 60 trials (from left to right). Lm is the masker level in a 1-Hz wide band relative to the sound level at the audiometric threshold at fs.

Results

Estimation of auditory filter shapes

A rounded-exponential auditory-filter model with three parameters, pl, pu and K, was used in order to summarise information about the auditory-filter width and asymmetry around the tip. Since this simple model does not consider the typically flatter tails, the results for the 0.4|0.4 notch were not included for the analysis. For each fs, the thresholds for the remaining eight notches were taken as input for the model. The values of pl and pu are shown for each subject in the left panels of Fig. 2. Normal-hearing subjects would have values around 30 to 40, lower p-values indicating a broader auditory filter.

The loudness model for hearing-impaired subjects of Moore and Glasberg (2004) relates the values of pl and pu to the outer hair cell loss (OHCL). The right panels of Fig. 2 show these relations, making it easier to compare the individual results with what would be expected for a typical cochlear hearing loss. OHCL was estimated based on pl only (red lines), pu only (blue lines) and the resulting equivalent rectangular bandwidth (purple lines). For a typical cochlear hearing loss, OHCL would be about 90% of the audiometric threshold.

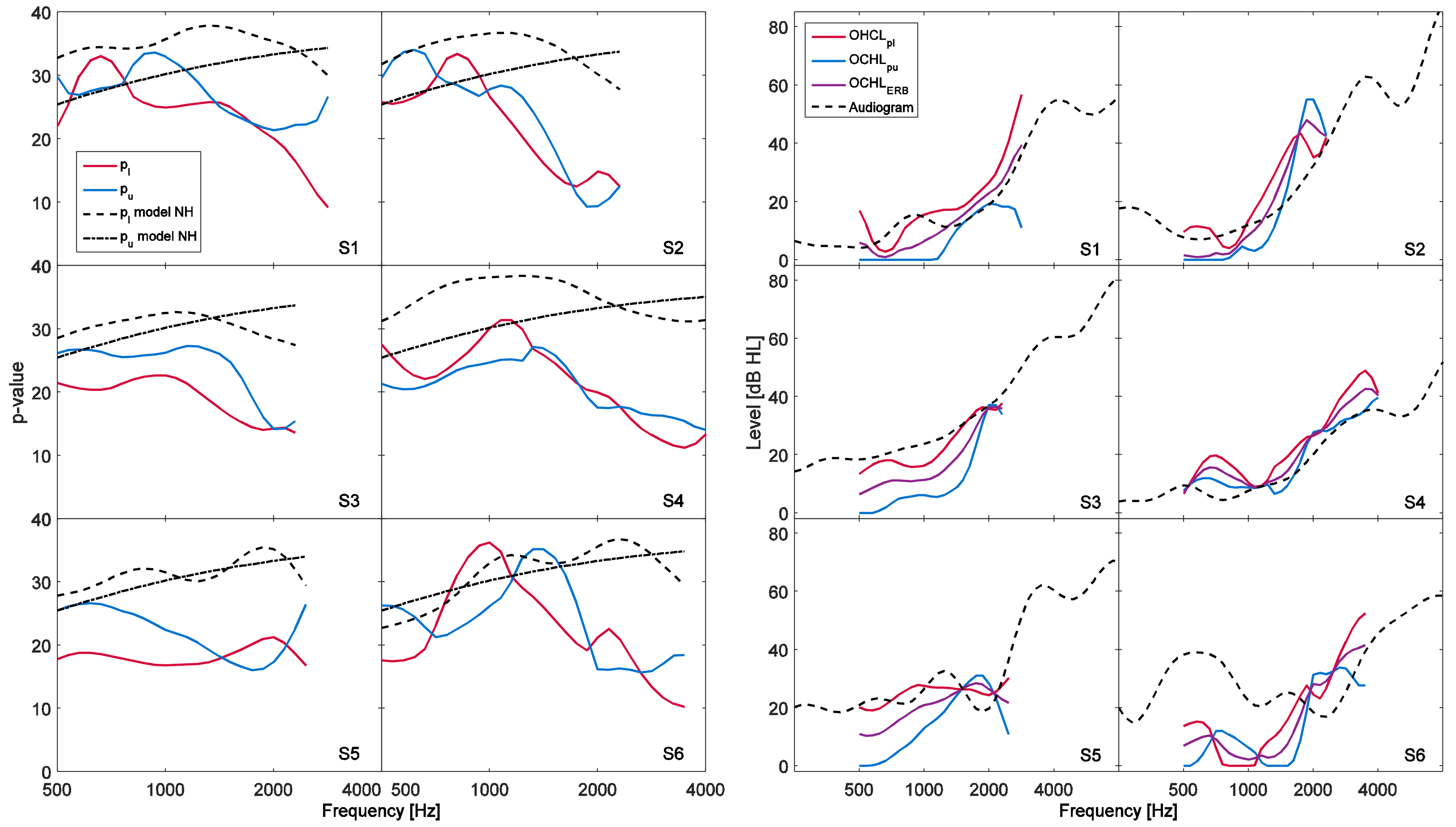

Fig. 2: Estimated auditory filter shapes. The two columns on the left show p-values characterising the slopes, and the two columns on the right show derived values of OHCL. Left: Red lines show values for pl, blue lines for pu, dashed and dash-dotted lines model values for normal hearing. Right: OHCL values derived from pl only (red lines), pu only (blue lines), and from the resulting equivalent rectangular bandwidth (purple lines). Dashed lines show the audiometric thresholds.

Validation

The 0.2|0.2 notch width was re-tested in a separate run to assess possible learning effects. The differences between test and re-test are shown in Fig. 3 (left panel). The average difference was -0.1 dB and the root mean square difference (RMSD) was 1.4 dB.

The overall difference between the thresholds for the 2-up/1down 2AFC method and the ML method was 0.3 dB and the RMSD was 2.5 dB. Values for single notches and subjects are shown in Fig. 3. (right panel).

The 0.2|0.2 notch width was tested twice with 2-up/1down 2AFC runs, in the 2nd and 6th runs (other notches in random order). The difference between the two thresholds was less than 1 dB for every subject with a mean of 0.0 dB and an RMSD of 0.5 dB.

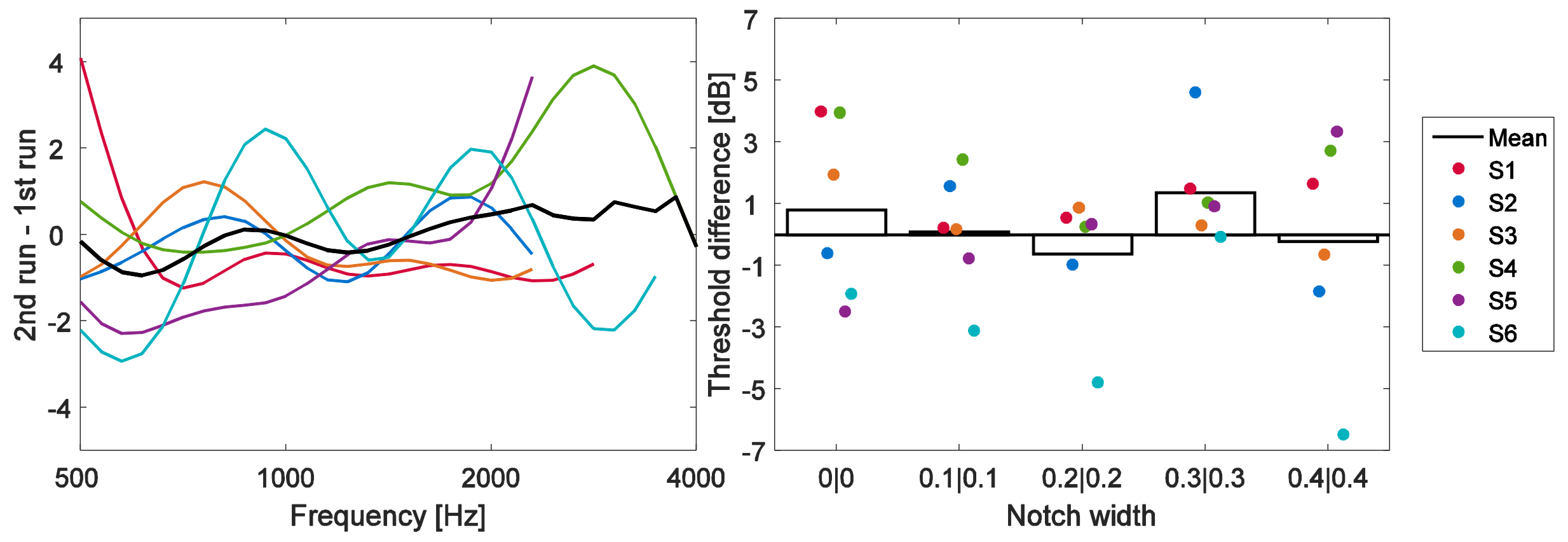

Fig. 3: Differences between runs and methods. Means across subjects are shown by black lines or bars and individual results are in colour. Left: [Threshold for 2nd ML run] – [threshold for 1st run] for 0.2|0.2. Right: [Threshold estimate for 2up/1down method] – [estimate for ML procedure] at 1.4 kHz

Discussion

The difference between the second and first ML runs was small and there was no systematic across-frequency difference for any subject, suggesting that there were no learning effects. The RMSD of 1.4 dB is acceptably small but may be further improved by including more trials per notch. The ML estimates were close to the estimates obtained using a conventional 2up/1down 2AFC method. The masker level at threshold was marginally higher for the ML method for 5 of the 6 subjects, as would be expected from the fact that the 2up/1down method tracks the 71%-correct point while the ML method was based on 50%-correct points.

Except for the lower frequencies for S6, the auditory-filter shapes agreed well with what would be expected from the audiogram. When comparing to the audiogram, it should be noted that the ML audiogram used here (Counting ML of Schlittenlacher et al. 2018a) yields a slightly lower threshold than a traditional procedure, and that audiograms in general have a variability with standard deviations of about 5 dB between methods, headphones and experimenters.

The upper and lower slopes agreed well for S2 and S4. The upper slope was slightly steeper than the lower slope for S1, and systematically steeper at low to mid-frequencies for S3 and S5, suggesting asymmetric auditory filters.

S6 reported having a burst eardrum twice 20 to 30 years ago. Although more tests are needed to independently confirm a diagnosis of a conductive hearing loss up to about 1.5 kHz, the auditory filter shapes suggest so. None of the other subjects reported anything that would hint at a conductive or neural hearing loss.

The levels chosen by the ML method will be analysed with regard to their loudness to check if higher masker levels (to allow testing of subjects with greater hearing loss) can be used without modifying the procedure, or whether additional measures are necessary to prevent uncomfortably loud sounds.

It needs to be determined if fewer trials would result in a similar accuracy, although the test is already short compared to conventional methods. The test could be combined with ML methods for determining the audiogram (Schlittenlacher et al., 2018a) and for assessing the edge frequency of dead regions (Schlittenlacher et al. 2018b) to form an automated test battery that may improve initial fits of a hearing aid.

Summary

The proposed ML method gives accurate threshold and auditory-filter estimates in a short time. The threshold estimates agreed in repeated runs and agreed with those obtained by a conventional 2up/1down procedure. OHCL estimates were close to what would be expected from the audiogram and a cochlear hearing loss. Some subjects had asymmetric auditory filters with a steeper upper slope. The ML method takes about as long as conventional methods for two signal frequencies and the same number of notches, but the ML method produces estimates across 2-3 octaves.

Acknowledgments

This work was supported by the Engineering and Physical Sciences Research Council (UK, grant number RG78536).

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