Frequency selectivity improvements in individual cochlear implant users with a biologically-inspired preprocessing algorithm

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The ability to distinguish between two sounds of different frequency is known as frequency selectivity, which can be quantified using psychoacoustic tuning curves (PTCs). Normal-hearing (NH) listeners show level- and frequency-dependent sharp PTCs, whereas frequency selectivity is strongly reduced in cochlear implant (CI) users. This study aims at (i) assessing the individual shapes of PTCs measured psycho-acoustically in CI users, (ii) comparing these shapes to those of simulated CI listeners, and (iii) improving the sharpness of PTCs using a biologically-inspired preprocessing algorithm. A 3-alternative-forced-choice forward masking technique was used to assess PTCs in eight CI users (with their own speech processor) and 11 NH listeners (with and without listening to a vocoder to simulate electric hearing). CI users showed large inter-individual variability in sharpness, whereas simulated CI listeners had shallow, but homogeneous PTCs. Furthermore, a biologically-inspired dynamic compression algorithm was used to process the stimuli before entering the CI users' speech processor or the vocoder simulation. This algorithm was able to partially restore frequency selectivity in both groups, meaning significantly sharper PTCs than unprocessed.

INTRODUCTION

Frequency selectivity is an important characteristic of the individual listener's ability to perceive sounds. Psychoacoustic tuning curves (PTCs) can be used to estimate frequency selectivity in normal-hearing (NH) or hearing-impaired (HI) listeners. PTCs display the masking threshold – i.e., the level of a pure-tone masker that is necessary to render a specific target tone inaudible – as a function of different masker frequencies. NH listeners show sharp PTCs with slightly lower masking thresholds at the low-frequency tail (due to upward spread of masking, cf. Moore, 1978; Oxenham and Plack, 1998). HI listeners show broader PTCs than NH listeners. Their PTC shape can be considerably sharpened using a dynamic compression algorithm (Jürgens *et al.*, 2014), as used in hearing aids. In cochlear implant (CI) users, "spatial tuning curves" (Nelson *et al.*, 2011) can be used to assess the spatial selectivity of electric stimulation on single electrodes using a

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Proceedings of ISAAR 2015: Individual Hearing Loss – Characterization, Modelling, Compensation Strategies. 5th symposium on Auditory and Audiological Research. August 2015, Nyborg, Denmark. Edited by S. Santurette, T. Dau, J. C. Dalsgaard, L. Tranebjærg, and T. Andersen. ISBN: 978-87-990013-5-4. The Danavox Jubilee Foundation, 2015.

similar paradigm to PTCs in acoustic hearing. These spatial tuning curves are not being measured using the CI user's personal speech processor, but using a research interface, which allows controlled stimulation of single electrodes. Spatial tuning curve shapes were found to be highly individual across CI users (Nelson *et al.*, 2011). A comparison to PTCs in NH and HI listeners is difficult, because such a comparison would require exact mappings of electric current to acoustic level and mappings of electrode location to acoustic frequency. Furthermore, spatial tuning curves (measured using a research interface) do not necessarily reflect the frequency selectivity of the CI user in their everyday life, because their speech processor and sound coding strategy are not used.

For performing such a PTC comparison, experiment 1 of this study measured PTCs in simulated CI users using a vocoder. In experiment 2, the same psychoacoustic measurement is then performed with individual CI users, which means that PTCs are measured with acoustic stimuli presented via the CI user's own speech processor. This allows a direct comparison across individual CI users, but also comparisons to NH listeners and simulated CI users. Finally, the hypothesis is tested whether improvements of the PTC shape due to preprocessing with a multi-channel dynamic compression algorithm (Meddis *et al.*, 2013) are possible in both simulated and actual CI users.

METHODS

Subjects and procedure

Eleven NH subjects (22–30 years, average age of 26 years) acted as the simulated CI listeners and were measured using Sennheiser HDA200 headphones listening through a software-implemented vocoder (adapted from Bräcker *et al.*, 2009, see below). Eight actual CI listeners (seven postlingual and one prelingual deafened, see Table 1, average age of 42 years) participated in the study. These CI users were presented with acoustic sounds using an audio cable connected directly from the sound card to the input of their sound processor.

ID	Age	Sex	Etiology	Duration of deafness (y)	CI usage (y)	Device
CI1	25	M	Ototoxic	17	8	Freedom Hybr.
CI2	23	F	Acute hearing loss	0.5	3	CP810
CI3	45	M	Lack of oxygen	44	0.6	CP910
CI4	19	F	Short hair cells	8	12	OPUS 2
CI5	64	M	Meningitis	49	1	CP810
CI6	46	F	Acute hearing loss	6	0.5	CP910
CI7	53	M	Since birth	7	6	CP910
CI8	63	M	Acute hearing loss	10	4	CP810

Table 1: Details about all participating CI listeners.

A 3-interval forced-choice (3-IFC) 1-up-2-down forward masking paradigm was used to determine the individual masking thresholds for pure-tone maskers with 7 frequencies relative to (0.5, 0.7, 0.9, 1.0, 1.1, 1.3, and 1.7 times) the fixed frequency of the 2-kHz pure-tone target. The target level was fixed at 10 dB sensation level (SL) and was determined for each listener beforehand using the same 3IFC method. The 106-ms masker was followed by 10 ms of silence and the 16-ms target tone. Three repetitions were averaged to obtain one masking threshold.

BioAid processing

BioAid (Meddis *et al.*, 2013) is a multi-channel dynamic compression algorithm that mimics two essential mechanisms in the healthy auditory system. The signal processing flow is shown in Fig. 1. Nine different frequency channels with half-octave-wide Butterworth filters at half-octave spacing were used. The first mechanism of BioAid is the instantaneous compression of the basilar membrane which is technically realized by an instantaneous ‘broken-stick’ compression. The second mechanism is the reflex of the medial olivocochlear complex which is realized by a slow and time-delayed feedback loop using a time constant of 50 ms. The latter process is called delayed feedback attenuation control (DFAC) in the algorithm and controls the attenuation adaptively in each channel.

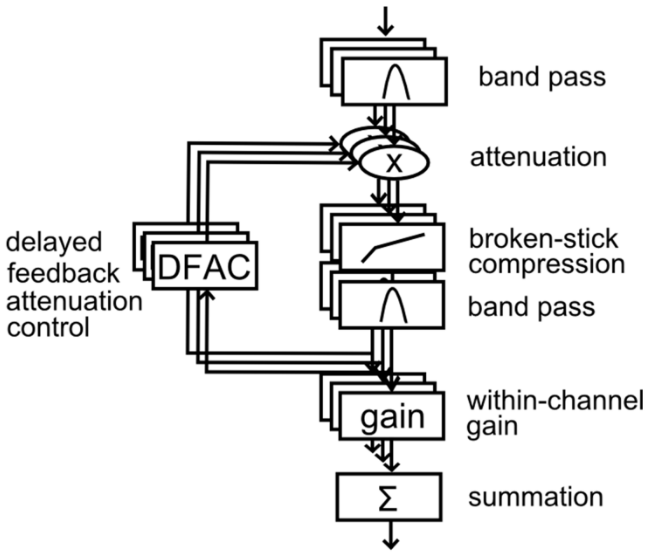

Fig. 1: Signal processing structure in the BioAid algorithm, different layers symbolize different frequency channels.

Both physiological mechanisms are missing in CI listeners, which is why their imitation might improve or even restore frequency selectivity. Both the DFAC and instantaneous compression consist of an activation threshold that is personalized for each listener.

CI simulation and measurement conditions

A vocoder mimicking details of the signal processing and the physiology of CI users (Bräcker *et al.*, 2009) was used for simulating CI users with NH listeners. This vocoder was structured to resemble the implant type of a Cochlear Contour Advance electrode array with 22 electrodes. PTCs were measured for simulated and actual CI users in three conditions: unprocessed (i.e., vocoded-only for simulated CI listeners), BioAid without and BioAid with instantaneous compression. In addition, NH listener's PTCs were measured without vocoder and BioAid as a reference.

RESULTS

Figures2 and 3 show PTCs as masker threshold levels in dB SL, which means that the zero line indicates the absolute threshold of the target tone. Circles indicate the averages over all three measurement repetitions for this masker frequency, while error bars indicate one standard deviation. PTCs were fitted using a 2nd order rounded exponential (ROEX) fit (Patterson *et al.*, 1982).

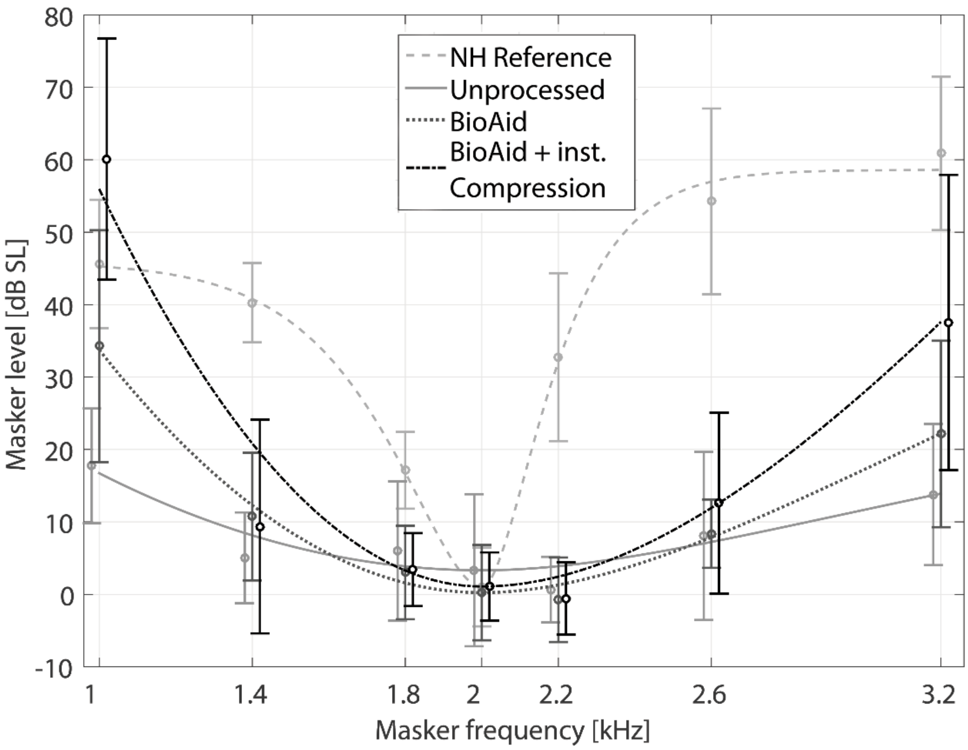

Fig. 2: Averaged group PTCs of all 11 simulated CI listeners: Masker level in dB SL as a function of masker frequency in kHz.

Experiment 1 – Simulated CI listeners

Figure 2 shows average masking thresholds and resulting PTCs averaged across simulated CI listeners. The NH reference PTC (gray dashed line) is relatively sharp in agreement with studies from the literature (e.g., Moore, 1978). The unprocessed

CI simulation (realized using the vocoder only, gray continuous line) shows a very flat shape. BioAid without instantaneous compression (black dotted line) shows small improvements in frequency selectivity in terms of a sharper PTC curve and a higher masking threshold at the outer-most masker frequencies (1 and 3.2 kHz). The improvement is stronger using BioAid with instantaneous compression (dashed-dotted line).

Experiment 2 – Actual CI listeners

Individual PTCs for actual CI listeners showed high variability among subjects (Fig. 3). In most cases, the unprocessed condition (grey continuous lines) resulted in a relatively flat PTC shape (similar to the unprocessed PTC of simulated CI listeners, see Fig. 2). High variability in PTC shape can also be observed regarding the effect of preprocessing the stimuli with BioAid. BioAid without instantaneous compression resulted in slightly sharper PTCs for some CI listeners (CI2, 3, 4, 6, and 8), while others showed no change (CI1, 5, and 7). For BioAid with instantaneous compression (dashed-dotted line), the PTC shape was strongly (CI2, 3, and 4), modestly (CI1, 5, 6, and 8) or not at all (CI7) affected by the algorithm. Thus, BioAid had a much stronger frequency selectivity restoration effect with than without instantaneous compression, especially in terms of higher masking thresholds at outlying masker frequencies (1, 1.4, 2.6, and 3.2 kHz).

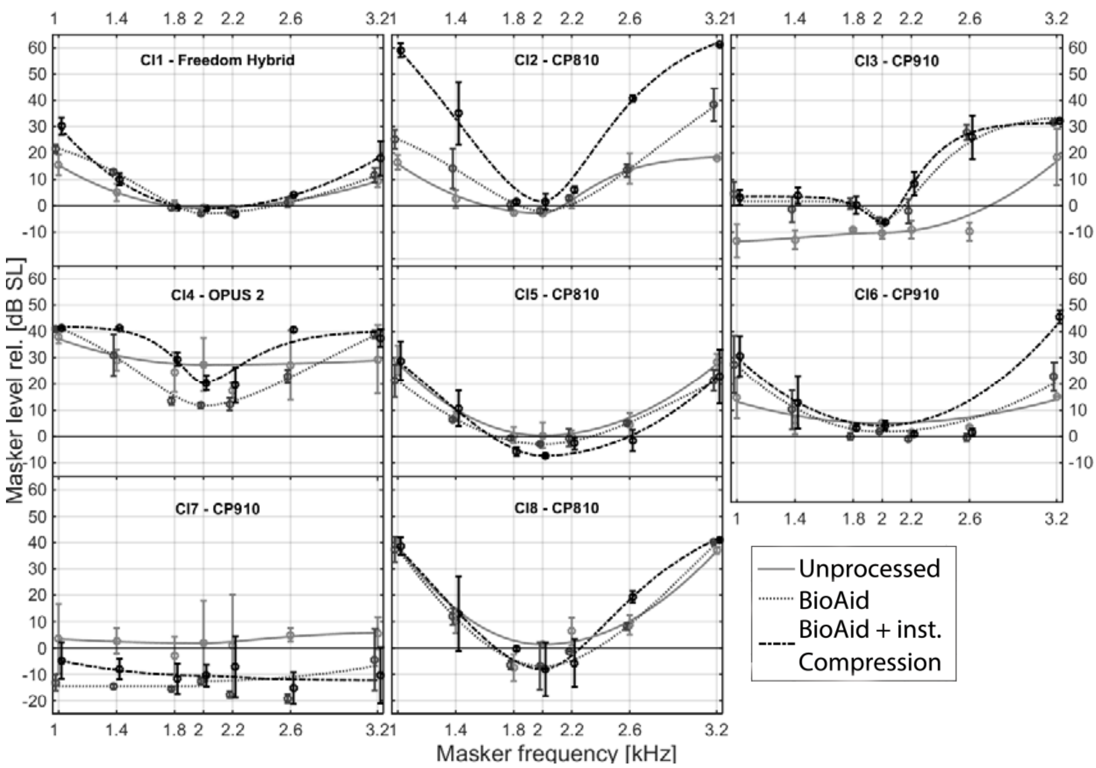

Fig. 3: Individual PTCs of 8 actual CI listeners in three conditions: relative masker level in dB SL as a function of masker frequency in kHz.

Statistical comparisons

Figure 4 shows two measures to quantify the sharpness of PTC shape: D_{PTC} (cf. Lecluyse *et al.*, 2013) and Q_{10dB}. D_{PTC} is a depth measure, in dB, and is the difference between the mean of all four outlying masker frequencies and the mean of the three centre masker frequencies. This measure is suitable for capturing the large-scale shape of the PTC. Q_{10dB} is the ratio between the centre frequency and the bandwidth 10 dB above the tip of the curve. For relatively flat PTCs, it captures variations only near the centre frequencies and is therefore a small-scale measure for PTC shape comparisons. The Friedman-test was used for statistical comparisons.

For the simulated CI listeners, D_{PTC}s were significantly different between the unprocessed condition and both BioAid conditions ($p < 0.01$), as well as significantly different between both BioAid conditions ($p < 0.05$). No significant difference was found between BioAid with instantaneous compression and the NH reference ($p > 0.1$), implying that the PTC sharpness (as measured using D_{PTC}) was fully restored. Significant differences in Q_{10dB} were found between the unprocessed and both BioAid conditions ($p < 0.01$). However, the NH reference condition showed a highly significant difference to all other conditions ($p < 0.01$). For the actual CI listeners, a significant difference between the unprocessed and BioAid with instantaneous compression condition was found both regarding D_{PTC} and Q_{10dB} ($p < 0.05$). There was no statistical difference in D_{PTC} or Q_{10dB} between unprocessed and BioAid without instantaneous compression in actual CI listeners.

DISCUSSION

Similar PTC shapes were observed across simulated CI listeners, in contrast to the very individual PTC shapes across the actual CI listeners. This large variability is in line with CI listeners' spatial tuning curves reported in Nelson *et al.* (2011). Different physiological factors, such as spatial spread of the electric field, number and distribution of auditory nerve fibers and the individual electric dynamic range, may have contributed to this high degree of individuality. However, also different signal processing schemes (four different devices from two different manufacturers) may have contributed as well. These factors can, in principle, be implemented also in the vocoder being used in this study (Bräcker *et al.*, 2009) for a systematic investigation of how strong the influence of these factors is on the PTC shape.

In line with earlier findings in HI listeners (Jürgens *et al.*, 2014), the PTC shape was sharpened in all simulated CI users and in 7 out of 8 actual CI users due to the algorithm BioAid. This highlights that frequency selectivity can be improved independently of CI manufacturer and device. The introduction of the D_{PTC} measure revealed that masking threshold increases were mainly present at remote masker frequencies. Frequency selectivity changes at nearby masker frequencies were limited, as the Q_{10dB} measure showed. Two different mechanisms in BioAid are responsible for the improvements in frequency selectivity, which can be separated by the two BioAid processing conditions tested in this study. The frequency-selective DFAC attenuates the masker, but leaves the target tone almost unchanged

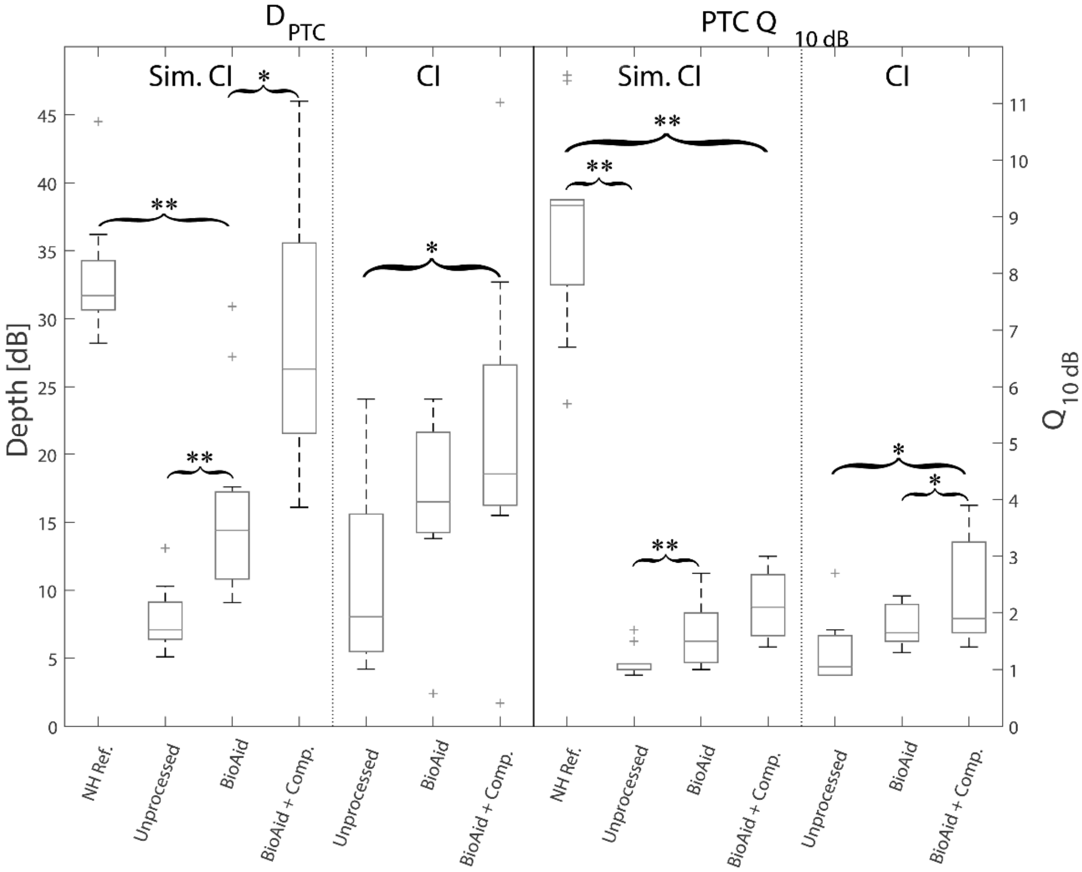

Fig. 4: Boxplots for simulated and actual CI listeners: the horizontal line within the box indicates the median; edges are the 25th and 75th percentiles, whiskers the most extreme data points and outliers are shown as plus signs. Significance symbols indicate $p < 0.05$ with * and $p < 0.01$ with **.

in amplitude if target and masker fall in different frequency channels (i.e., for remote masker frequencies). Thus, the masking effect for maskers with remote frequencies is diminished allowing higher masker levels at threshold. If masker and target fall in the same frequency channel both are attenuated due to the DFAC and masker thresholds are virtually unchanged. Enabling instantaneous compression in addition to the DFAC (in BioAid + instantaneous compression) diminishes the masking effect for remote-frequency maskers further, because the masker (higher in level) is being compressed, whereas the target tone is not.

It is important to consider the different compression stages in both the simulated and the actual CI listeners. While simulated CI listeners use only one compression stage in BioAid with instantaneous compression (in addition to their healthy basilar membrane compression), actual CI listeners use up to three compression stages (BioAid with instantaneous compression, a broadband automatic gain control or adaptive dynamic range optimization (ADRO) preceding, and instantaneous compression within their sound coding strategy). These differences are most likely responsible for the smaller frequency selectivity improvements for actual CI listeners than for simulated CI listeners.

It is conceivable that the direct implementation of BioAid's mechanisms into a CI coding strategy could enlarge their effect on frequency selectivity even further. This might especially prove useful for programs that are fitted for listening to music.

CONCLUSIONS

PTCs of simulated CI users were found to be broader than those obtained with the NH reference group. PTCs of the actual CI users were also broader, but varied strongly across users. In both groups, the multi-channel dynamic compression algorithm BioAid was able to partially restore the sharpness of PTCs, except for one CI user (CI7). This indicates that frequency selectivity can be improved using a compressive processing preceding the CI speech processor. Future research should investigate the implementation of BioAid's algorithm structure into a music coding strategy for cochlear implants.

ACKNOWLEDGEMENTS

This study was supported by DFG cluster of Excellence “Hearing4all” and the Scholarship for ISAAR. Special thanks to Ray Meddis for fruitful discussion and Torsten Dau for helpful comments on an earlier version of the manuscript.

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