Across-electrode processing in CI users: a strongly etiology dependent task

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To investigate across-electrode processing in cochlear-implant (CI) users, we established an experimental setup that allows measuring comodulation masking release (CMR) using controlled electrical stimulation of auditory nerve fibers. In this paper we present results of a flanking-band type of CMR experiment with uncorrelated (UC) vs. comodulated (CM) masker components. To deal with the large current spread in electrical stimulation that may introduce additional masking especially in the UC condition, we now compare two different electrode configurations: proximate vs. remote alignments of flanking bands in reference to the on-signal band. Results of 18 test subjects revealed no significant difference between CMR[UC-CM] magnitudes across these two conditions (p = 0.3), whereas outcomes varied strongly across test subjects. To highlight different groups of performers, a hierarchical cluster analysis was conducted. N = 5 CI users showed no or even negative CMR. The majority of N = 9 CI users exhibited positive and significant CMR (around 3 dB). Finally, a subset of N = 4 CI users showed considerable CMR magnitudes (6-10 dB). Etiology was a good indicator for the remaining individual CMR capabilities.

INTRODUCTION

The normal-hearing (NH) auditory system provides elaborated strategies to segregate different sounds with overlapping spectra occurring at the same time, usually an unsolvable task for cochlear-implant (CI) users. An important neural mechanism in this context is across-frequency processing: There is good evidence that the auditory system is able to make comparisons across the outputs of auditory filters (Moore, 2012). Many natural sounds exhibit highly-correlated temporal envelope fluctuations in different frequency bands. Common amplitude fluctuation across-frequency facilitates comodulation masking release (CMR) and may also contribute to auditory grouping (Bregman, 1990). CMR illustrates the fact that detectability of a sinusoidal signal masked by a narrow-band masker can be markedly improved by simultaneously presenting additional maskers at frequencies remote from the signal

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Proceedings of ISAAR 2013: Auditory Plasticity – Listening with the Brain. 4th symposium on Auditory and Audiological Research. August 2013, Nyborg, Denmark. Edited by T. Dau, S. Santurette, J. C. Dalsgaard, L. Tranebjærg, T. Andersen, and T. Poulsen. ISBN: 978-87-990013-4-7. The Danavox Jubilee Foundation, 2014.

frequency, provided the envelope fluctuations across frequencies are coherent (Hall *et al.*, 1984).

Two different types of CMR measurements are established in acoustic experiments: band-widening and flanking-band type of CMR experiments (for a review, see Verhey *et al.* (2003)). We concentrate on the latter type (see methods section).

Recent stimulation strategies in cochlear implants are often based on continuous interleaved sampling (CIS): In simple terms, the signal first goes through a set of bandpass filters which divide the acoustic waveform into different frequency channels. The envelopes of each channel are then detected by rectification and low-pass filtering according to a Hilbert transform. Current pulses are generated with amplitudes proportional to the envelopes of each frequency band and transmitted to multiple intracochlear electrodes. In CIS strategies stimulation is usually realized sequentially and not simultaneously across channels. The pulse rate is usually constant.

As CMR is sensitive to low-frequency level fluctuations represented by the temporal envelope of the signals (e.g., Epp *et al.* (2009)) and such low-frequency envelope fluctuations are usually well perceived by CI users (Shannon, 1992), our assumption was that CMR in CI users may exist. In a former publication we addressed this issue (Zirn *et al.*, 2013). There we described how we stimulated relatively apical electrodes with fixed distance between the flanking- and on-signal band-electrodes. As a result we could show that approx. 30% of CI users (7/21) were able to benefit from correlations in a masker in terms of facilitated target detection. The pattern of masked detection thresholds across test subjects, revealing peripheral masking due to current spread, cannot explain the whole effect: The difference of detection thresholds between the uncorrelated and the comodulated condition resulted from a lower detection threshold in the comodulated condition in the subjects with considerable CMR magnitudes. Peripheral masking due to current spread would provoke more masking energy in the on-signal band in the uncorrelated condition and therefore higher detection thresholds in this condition.

To embrace this issue from another perspective we now compare the results of two different configurations of active electrodes: proximate and remote flanking bands in reference to an on-signal masker. This is explained in more detail in the next section.

METHODS

A CMR flanking-band experiment was adapted to electrically-induced hearing. We orientated ourselves to a typical acoustic type of flanking-band CMR experiment. Here, the masker consists of several narrow-band maskers; one at the signal frequency and one or more narrow-band maskers spectrally separated from signal frequency. The masker components are amplitude-modulated either uncorrelated or correlated (comodulated) and the difference of masked detection thresholds of the embedded target sinusoidal signal determines CMR. The underlying definition that can be investigated with this setup is the uncorrelated (UC)-comodulated (CM) CMR[UC-

CM] definition. The masker component at signal frequency is termed on-signal band (OSB) and the other components spectrally remote to the OSB are called flanking bands (FB). To achieve relatively high CMR magnitudes up to 12-13 dB in normal-hearing listeners (Epp *et al.*, 2009) four FBs are often used.

Adapted to electrically induced hearing we stimulated across five intracochlear electrodes. The medial electrode (#14) contained OSB and target. FBs were streamed to proximate or remote four electrodes (see Table 1).

Condition	Electrode configuration
Proximate flanking band electrodes	18, 16, 12, 10
Remote ¨ ¨ ¨	22, 20, 8, 6

Table 1: Addressed electrodes in different test conditions

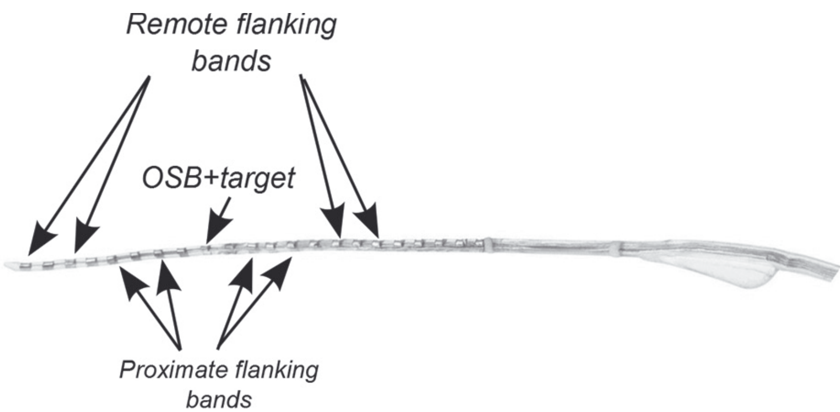

Fig. 1: Electrode configuration in different test conditions. The implant shown is a CI422 by courtesy of Cochlear Ltd.

The required addition of two uncorrelated signals (OSB plus sinusoidal target signal) was conducted in with the original signals (with carrier frequency; pointwise addition with constructive and destructive interference depending on phase relationships of OSB and target; center frequencies orientated at the usual frequency table of the fitting software – Custom Sound Version 3.2, Cochlear Ltd. with 22 active channels). For determination of the overall sound pressure level when adding two non-coherent sounds, see Eq. 1.

$$L_1 + L_2 = 10\log_{10}(10^{L_1/10} + 10^{L_2/10})\ \ [\text{dB}] \qquad \text{(Eq. 1)}$$

After determination of the envelope using a Hilbert transform, the signal was then used to modulate a biphasic pulse train and streamed to electrode #14. Additionally four flanking bands (either uncorrelated (Fig. 1) or comodulated (Fig. 2) to the OSB; all biphasic current pulse trains) were presented to proximate or remote electrodes (see Fig. 2).

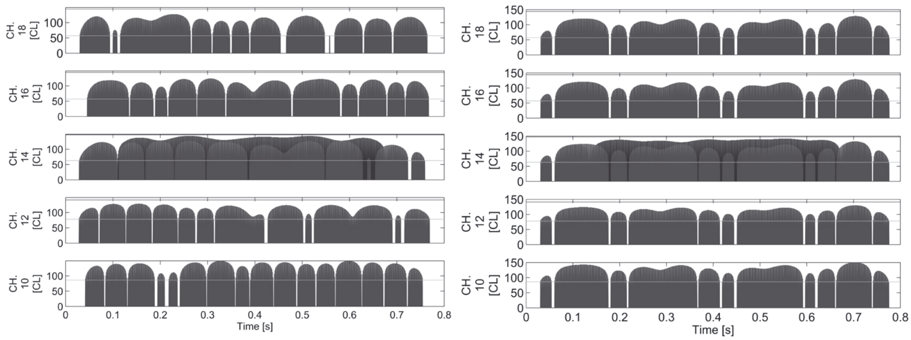

Fig. 2: Superimposed stimulation sequences with and without target (+10 dB signal-to-noise ratio) in the proximate uncorrelated condition (left) and comodulated condition (right). Shown are the positive phases of biphasic current pulse trains that are streamed to five CI electrodes. CL: Cochlear current levels. Horizontal lines indicate electrode-specific current levels at individual hearing threshold levels (T-levels – lower lines) and most comfortable levels (C-levels – upper lines).

Duration of the target was 0.6 sec, OSB duration 0.8 sec. The target was temporally centered in the OSB. All stimuli (also FBs) were ramped up and down at signal onset and offset (100-ms $\cos^2$ ramps).

Procedure

A three-interval, three-alternative forced-choice procedure with adaptive signal-level adjustment was used to determine the masked threshold of the target. CI users had to indicate which of the intervals contained the signal. A graphical user interface with visual feedback was therefore used. The signal level was adjusted according to a two-down, one-up rule to estimate the 70.7% point of the psychometric function (Levitt, 1971). The initial step size was 8 dB. After every second reversal the step size was halved until a step size of 1 dB was reached. The run was then continued for another four reversals. From the level at these last four reversals, the mean was calculated and used as an estimate of the threshold. The final threshold estimate was taken as the mean over two threshold estimates.

Stimulation Hardware

Streaming of stimuli was achieved using the Nucleus Implant Communicator (NIC) and the Nucleus Matlab Toolbox from Cochlear Ltd. Envelopes were inserted in the frequency-time matrix and processed with the following steps of the Advanced Combination Encoder stimulation strategy of Cochlear with 5 maxima, 900 pulses per channel per s, 25-μs pulse width, monopolar stimulation.

Participants

We included 18 test subjects that were provided with cochlear implants from Cochlear Ltd. unilaterally (N = 12) or bilaterally (N = 6). In case of a bilateral CI user, the ear with better performance was selected for the experiment (based on results in Freiburg monosyllables and Oldenburger Sentence test in steady-state interference). Mean age of participants was 55 yrs ± 15. Cochlear implants were types CI24R, CI24RE, CI422, or CI512. All of them are fully compatible with NIC streaming.

RESULTS

Mean masked detection thresholds are shown in Fig. 3. Across all test subjects, a highly-significant release form masking occurred in the proximate condition (3.2 dB ± 0.8, Wilcoxon signed-rank test: $p = 0.006$) and significant magnitudes in the remote condition (4.2 dB ± 0.3, $p = 0.02$).

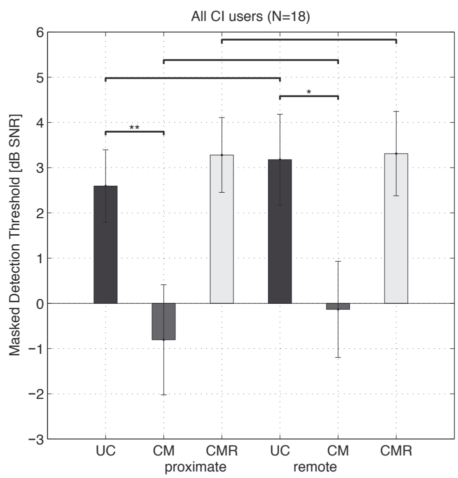

Fig. 3: Mean masked detection thresholds and CMR magnitudes in the proximate (left) and remote (right) condition. Error bars depict one standard error of the mean.

The difference of CMR magnitudes in the proximate vs. remote condition was not significant (Wilcoxon signed-rank test: $p = 0.3$). The same holds for differences of underlying masked detection thresholds in the UC proximate vs. remote condition (p=0.1) and CM proximate vs. remote condition ($p = 0.7$) condition. To deal with the large inter-individual variability across test subjects, a hierarchical cluster analysis into three clusters was calculated. The three clusters revealed groups of CI users that performed very differently. A group of N = 5 test subjects showed no release of masking or even negative values (cluster 1). The majority (N = 9) showed considerable CMR magnitudes of approx. 3 dB (in the proximate as well as in the remote condition – cluster 2). A subgroup of N = 4 CI users showed larger mean CMR magnitudes with better detection thresholds.

DISCUSSION

CMR magnitudes in the proximate flanking-band condition correspond to that found on more apical electrodes in an earlier similar test setup (Zirn *et al.*, 2013). The position of flanking bands (proximate or remote) had minor impact on CMR outcomes (Wilcoxon signed-rank test: p = 0.3). A mainly peripheral explanation for the measured effect as a consequence of masking due to current spread is therefore unlikely. Furthermore, beating between the carrier frequencies of two masker bands cannot occur in constant rate envelope-based electrical stimulation. This finding corroborates our notion that a subset of CI users is able to effectively make comparisons across the stimulation sites. CMR magnitudes were dependent on etiology:

Etiology	**CMR[UC-CM] prox**
Progressive	0.7 dB $\pm$ 1.3 (N = 7)
Congenital	4.3 dB $\pm$ 1 (N = 6)
Acute hearing loss	5.8 dB (N = 1) (N = 6)
Otitis media	6 dB $\pm$ 0.5 (N = 3) (N = 6)
Noise trauma	10 dB (N = 1)

Table 2: Etiologies and corresponding CMR magnitudes

Our hypothesis: Across-electrode processing can be impaired by long-term hearing loss and/or specific etiologies that implicate retro-cochlear impairments.

Results are only valid for test-specific stimuli with direct controlled stimulation. Amplitude comodulation across electrodes is altered by CI signal processing when stimulated acoustically.

An aspect that so far cannot be addressed based on the available data-set is the influence of individual C-levels, dynamic range, or spread of spatial excitation measured with electrically-evoked compound action potentials. The large inter-individual variability of results makes a clear statement in this context difficult. We therefore try to increase the number of test subjects.

ACKNOWLEDGMENTS

This work was supported by Cochlear Ltd., Dr. H. Hessel (IIR-73; CMR in CI users CRDL) and the German Federal Ministry of Education and Research within the Munich Bernstein Center of Computational Neuroscience (reference number 01GQ1004B).

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