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Effects of pulse rate and electrode on combined within-channel forward and backward masking in cochlear implant users

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Abstract

Cochlear implants restore hearing in profoundly hearing-impaired or deaf individuals by stimulating the auditory nerve with electric pulses. One remaining problem is a deficit in speech perception that occurs in noisy situations and is partially caused by masking originating in the cochlea. This work examined the time course of electrical masking of a single-pulse target by 300 ms maskers for two masker pulse rates (200 and 1000 pulses/s) and apical (el. 2) and basal (el. 8) electrodes. The psychoacoustic recovery function was sampled at four points, corresponding to time offsets of 1.5, 3.0, 6.0 and 100 ms after the forward masker and/or before the backward masker. Generally, there was more forward masking (recovery time constant $\tau_1 = 336$ ms) than backward masking ($\tau_2 = 206$ ms) and no differences in the time course between the rates and electrodes were found. Pulse rate and electrode had significant overall effects (in terms of dynamic range), with more masking occurring for 200 pps and electrode 8. Finally, considerable individual differences were observed.

I. Introduction

Around 1.5 billion people worldwide live with hearing loss. A significant proportion of them (5.5%) lives with moderate to severe hearing loss that in some cases can be treated with hearing aids or other acoustic devices [1]. Furthermore, cochlear implants (CI) can often be used to treat severe-to-profound hearing loss or deafness. One of the primary challenges associated with CIs is that normal hearing cannot be fully restored. The intelligibility of speech in noisy environments and sometimes even in quiet conditions remains a challenge [2]. CI manufacturers use various coding strategies to convert the acoustic input to pulse sequences presented to the auditory nerve through the CI electrodes. Two of the key factors of these coding strategies are the per-electrode pulse rate and cochlear location (i.e. the CI electrode). Research has indicated that, at low rates of 100 to 300 pps, the sensitivity to temporal cues, particularly temporal pitch and interaural time difference, is optimal [3]. However, in most CI coding strategies far higher pulse rates of 1000 and more (e.g., CIS [4]) are chosen with the goal of better temporal sampling and mimicking normal firing of auditory neurons [5]. The effect of the pulse rate might furthermore depend on the place of the electrode inside the cochlea. A recent study found that there is a significant effect of electrode position, at least for bipolar stimulation, with the most basal electrodes producing more temporal masking than the apical electrodes [6]. Clinical coding strategies such as FSP or FS4 (-p) use constant high pulse rates on the basal electrodes, while on apical electrodes the pulse rate depends on the acoustic fre-

quency [7]. Impairments in speech intelligibility in noise, especially with multiple concurrent sound sources, can be attributed to the distortion of the acoustic signal in the electrode-neuron interface, particularly the unwanted flow of electrical current inside the fluid-filled cochlea. This leads to distortions in the frequency, time, and amplitude domains [8]. As a consequence, some crucial acoustic cues may be masked by perceptually irrelevant pulses and, hence, cannot be perceived by the CI listener. To date, forward masking has been investigated much more than backward or combined masking.
This study investigated combined single-electrode forward and backward masking in CI users to subsequently increase pulse efficiency in CI coding strategies. To this end, thresholds of masked and unmasked single-pulse targets were measured on electrode (el.) 2 and 8, with pulse rates of 200 and 1000, respectively.

II. Methods and materials

II.I. Participants

Four adult CI listeners (2 females, mean age 63 yr (SD = 4.64 yr), mean CI experience 8.2 yr (SD = 7.01 yr)) with six implanted ears participated in this study. All listeners used CIs produced by MED-EL GmbH (Innsbruck, Austria) with FLEX28, FLEXsoft, or Standard electrode arrays. Each ear had at least ten active electrodes. The average test time was ten hours per ear and the study was spread across two or more days. All listeners received an hourly pay for their participation.

II.II. Stimuli and apparatus

Figure 1, shows a schematic representation of the experimental stimuli. Note that for simplicity only positive phases are shown. Two unmodulated 300-ms pulse trains with rates of 200 pps (el. 2) or 1000 pps (el. 2 and 8) served as forward and backward maskers. Their amplitudes were fixed at 75% of the dynamic range (DR). In between, the target stimulus was a single pulse with an average per phase duration of 44.5 µs (for details, see Section II.III). Its amplitude was adjusted in the experiment. Maskers and target were always presented on the same electrode (within-channel masking) and both maskers had the same rate. The recovery function was sampled at four time points, corresponding to masker-target offsets t_1/t_2 (forward/backward) of either 1.53, 3.03, 6.00, or 100.00 ms. All pulses were biphasic, cathodic-leading, had no inter-phase gap, and were presented in monopolar mode.
All measurements were conducted using the ExpSuite software framework. CI listeners were directly stimulated (i.e., without CI speech processors) using the MAX interface manufactured by MED-EL together with the RIB2 library provided by the Institute of Ion Physics and Applied Physics of the Leopold-Franzens University (Innsbruck, Austria). The participants were seated in a quiet room and were visually shielded from the experimenter.

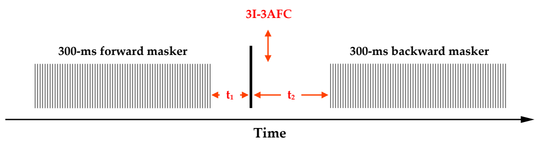

Figure 1: Stimulus consisting of forward masker pulse train, single target pulse (separated from forward masker by t_1 ms), and backward masker pulse train (separated from target by t_2 ms). Masker amplitudes were fixed while the target amplitude was adaptively adjusted in a three-interval three-alternative forced-choice (3I-3AFC) task (see Section II.III).

II.III. Procedure

All measurements were conducted one ear at a time. First, maximum comfortable levels were obtained for a single pulse at both tested electrodes using an informal adjustment procedure. This was done to ensure sufficient audibility of the single-pulse target in the masking experiment. If audibility was insufficient with the default phase duration of 26.7 µs (i.e., if the maximum comfortable level was not reached), the duration was increased for each CI listener individually. Importantly, the larger phase duration (44.5 µs on average across listeners) was finally used for both tested electrodes for consistency.
Second, for the unmasked condition, amplitude thresholds were obtained (in µA) for a single pulses target using a three-interval three-alternative forced-choice task and the weighted up-down staircase procedure [9] converging after eight turnarounds at 75% correct responses. The listeners indicated which of the three task intervals, visually highlighted on a computer screen, contained the target. Per electrode, at least four threshold measurements were obtained.
Third, masker stimulus fittings were obtained. In particular, per rate-electrode combination (REC), threshold and maximum comfortable level were measured.
Fourth, for the masked condition, amplitude thresholds were obtained (in µA) for the target masked by a combination of forward and backward masker with 12 t_1-t_2 combinations. Per combination, a single threshold was obtained using the same task and procedure as for the unmasked thresholds. The participants indicated which of the three visually cued intervals contained a stimulus that differed from the other two intervals.
For all threshold measurements, CI listeners were familiarized with the stimuli before starting data collection. All staircases were inspected for plausible convergence and repeated if necessary.

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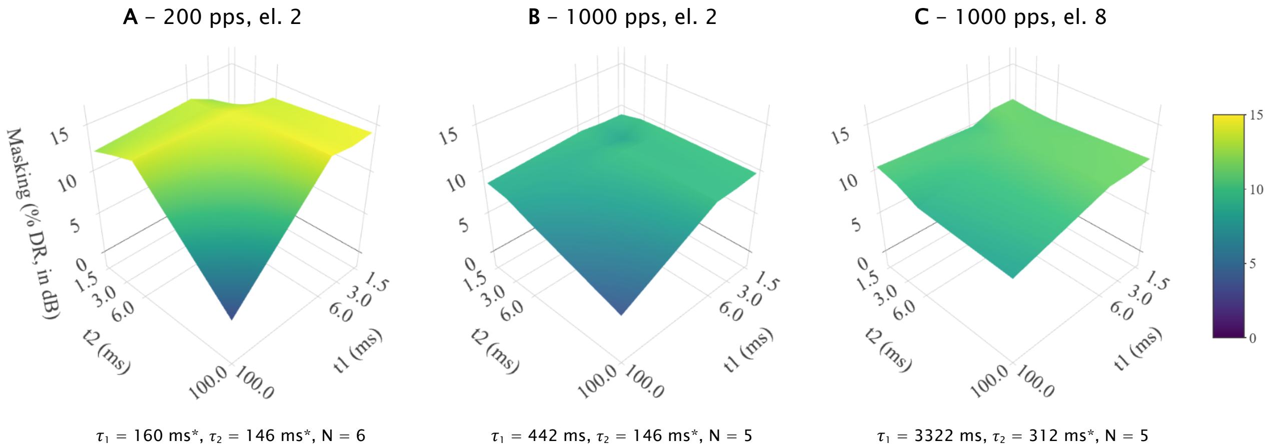

Figure 2: Masking, defined in decibels (dB) as the ratio of masked to unmasked single-pulse thresholds (all defined as proportions of the DR), against masker-target offsets (t_1 and t_2, see Section II.III) plotted on a logarithmic scale. Panels distinguish combinations of masker pulse rate and stimulation electrode (i.e., RECs). Per panel, recovery time constants and sample size are denoted. Significance is based on the t-statistic with 16 (200 pps) or 13 (1000 pps) degrees of freedom, respectively. * ... $p < 0.05$.

II.IV. Data processing and analysis

Amplitude thresholds were defined as the median of the last four turnarounds of each staircase, pooled across all staircases for a certain condition (i.e., four staircases and one staircase in the unmasked and masked condition, respectively). Subsequently, thresholds were expressed as proportions of the DR for better comparability across listeners [10]. Masking was quantified in decibels (dB) as the ratio of masked to unmasked thresholds.

Linear-regression analyses were performed to estimate the recovery time constants τ_1 (forward masking, t_1; continuous predictor) and τ_2 (backward masking, t_2; continuous predictor) as well as the effects of masker pulse rate and stimulation electrode (categorical predictors). Smaller τ's indicate faster masking decay. Due to the within-subjects design of the experiment, the ear was included as a categorical predictor to partition out the between-subjects variance [11]. To assess the maximum amount of masking (the intercept in statistical terms), the continuous predictors were shifted by 6 ms (see Section III.I) rather than centered on the mean as by default.

Data analysis was performed in R 4.3.3 using the packages *ConsReg* (linear regression constrained to positive τ's) and *boot* (bootstrapped confidence intervals). The significance level was 5%.

III. Results and discussion

III.I. Group effects

The raw masking averages are shown in Figure 2, separated into panels by REC, as a function of t_1 and t_2. Panel **A** shows masking levels up to 15 dB combined with a steep decay between 6.0 and 100 ms. In contrast, panels **B** and **C**, differing from panel **A** in masker pulse rate, both show less masking (maximum about 10 dB) and a shallower decay. The decay is particularly shallow for the more basal electrode 8 in panel **C**.

Masking was constant for offsets of 6 ms and less. Hence, all statistical analyses only included t's of 6 and 100 ms. In each panel of Figure 2, the τ's estimated with separate analyses per REC are denoted alongside the sample size N. Across RECs, the forward masking decay (τ_1) was significant only for 200 pps while the backward masking decay (τ_2) was always significant. Furthermore, maximum masking is strongest at a pulse rate of 200 pps (but decays faster than for 1000 pps). For 1000 pps, masking seems to decay slower at el. 8, if decaying at all.

The effects of pulse rate (at el. 2) and electrode (for 1000 pps) were statistically assessed with two separate analyses, each combining two RECs. For the pulse rate, no significant effects on the τ's were found ($t(30) \leq 1.16$, $p \geq .255$). It should be noted that this non-significance might be due to the small sample size. However, a significant overall effect ($t(32) = 4.53$, $p < .001$) was found at 1000 pps with masking levels 6.5 dB lower. The electrode had no significant effect on the τ's ($t(30) \leq 0.79$, $p \geq .437$), yet, a significant overall effect ($t(32) = 2.19$, $p = .036$) was found at electrode 8 with masking levels 2.2 dB higher. Again the lacking effect of τ appears due to the small sample size.

Since neither pulse rate nor electrode affected masking decay, an analysis was conducted with the full data set and the REC as categorical predictor to estimate the grand-average τ's. This analysis revealed more forward masking ($\tau_1 = 336$ ms, $t(51) = 2.22$, $p = .031$) than backward masking ($\tau_2 = 206$ ms, $t(51) = 3.62$, $p < .001$).

These findings are largely consistent with the results of Chatterjee et al. [6] obtained with a pulse-train target instead of a single-pulse target. They found shallower forward masking decay in CI listeners ($\tau_1 \approx 100$ ms) as compared to normal-hearing listeners. Still, the time constants estimated in the present study are considerably larger (about 150 ms to not decaying at all) which might be attributable to the different target stimuli. More research is necessary to assess this difference in detail.

III.II. Individual differences

Figure 3 shows the individual differences in masking for $t_1 = t_2 = 6$ ms and between RECs. The abscissa represents the individual ear, while the ordinate displays the regression-estimated masking in dB. The results reveal considerable variability between individual ears. Note that CI128 has not completed testing in the right ear. The effect of the pulse rate is visible for most ears (straigtforwardly in CI16 and CI129), but for some ears with a confounding effect of electrode (e.g., CI18).

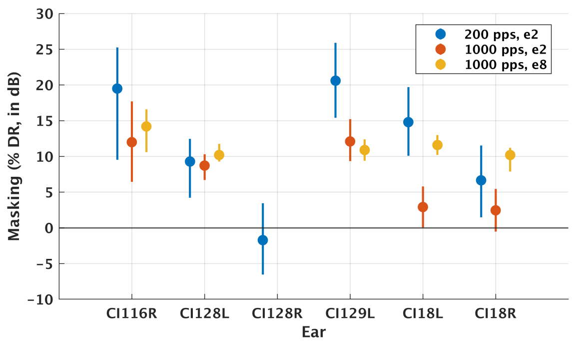

Figure 3: Individual differences in Masking for $t_1 = t_2 = 6$ ms per REC and tested ear (coded as participant ID [e.g., CI18] plus side). Markers denote regression fits alongside bootstrapped 95% confidence intervals (cf. Section II.IV).

IV. Conclusion

This study investigated the effects of pulse rate and electrode on extent and decay of combined within-channel forward and backward masking in CI users. Generally, there was a longer time constant of forward masking ($\tau_1 = 336$ ms) than backward masking ($\tau_2 = 206$ ms) and there were no differences in the time constant between the rates and electrodes. Pulse rate and electrode had significant overall effects, with more maximum masking occurring for 200 pps and electrode 8. Finally, considerable individual differences were observed, highlighting the need for individual assessment of masking in the development of future CI coding strategies. It is important to note that only a limited dataset was obtained so far, and further data is currently collected to quantify particularly the effect of pulse rate on masking decay.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board.

References

[1] World report on hearing, World Health Organization, 2021.

[2] W. Lamping, T. Goehring, *et al.* The effect of a coding strategy that removes temporally masked pulses on speech perception by cochlear implant users. *Hearing research*, 391:107969, 2020, doi:10.1016/j.heares.2020.107969.

[3] A. Ihlefeld, R. P. Carlyon, *et al.* Limitations on monaural and binaural temporal processing in bilateral cochlear implant listeners. *Journal of the Association for Research in Otolaryngology*, 16:641–652, 2015, doi:10.1007/s10162-015-0527-7.

[4] B. S. Wilson, C. C. Finley, *et al.* Better speech recognition with cochlear implants. *Nature*, 352(6332):236–238, 1991, doi:10.1038/352236a0.

[5] R. V. Shannon, R. J. Cruz, *et al.* Effect of stimulation rate on cochlear implant users' phoneme, word and sentence recognition in quiet and in noise. *Audiology and Neurotology*, 16(2):113–123, 2011, doi:10.1159/000315115.

[6] M. Chatterjee and A. M. Kulkarni. Recovery from forward masking in cochlear implant listeners depends on stimulation mode, level, and electrode location. *The Journal of the Acoustical Society of America*, 141(5):3190–3202, 2017, doi:10.1121/1.4983156.

[7] D. Riss, J.-S. Hamzavi, *et al.* Fs4, fs4-p, and fsp: A 4-month crossover study of 3 fine structure sound-coding strategies. *Ear and Hearing*, 35(6):e272–e281, 2014, doi:10.1097/AUD.0000000000000063.

[8] O. Macherey and R. P. Carlyon. Cochlear implants. *Current Biology*, 24(18):R878–R884, 2014, doi:10.1016/j.cub.2014.06.053.

[9] C. Kaernbach. Simple adaptive testing with the weighted up-down method. *Perception & psychophysics*, 49(3):227–229, 1991, doi:10.3758/BF03214307.

[10] C. M. McKay. Forward masking as a method of measuring place specificity of neural excitation in cochlear implants: A review of methods and interpretation. *The Journal of the Acoustical Society of America*, 131(3):2209–2224, 2012, doi:10.1121/1.3683248.

[11] J. M. Bland and D. G. Altman. Statistics notes: Calculating correlation coefficients with repeated observations: Part 1—correlation within subjects. *Bmj*, 310(6977):446, 1995, doi:10.1136/bmj.310.6977.446.