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Binaural processing in a new cochlear-implant paradigm inserting extra pulses with short inter-pulse intervals

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ABSTRACT

Cochlear-implant (CI) listeners face degraded selective hearing because they lack sensitivity to both interaural time difference (ITD) and pitch cues. One major reason is the replacement of the acoustic temporal fine structure by periodic high-rate pulse trains to avoid electric-field interactions. A second major reason is a perceptual limitation of CI listeners in the maximum pulse rate up to which ITD and pitch cues are salient. Recently, a new approach relying on inserting extra pulses with short inter-pulse intervals (SIPI pulses) into the high-rate carrier pulse trains has been shown to enhance ITD and pitch sensitivity while likely maintaining speech understanding. In this contribution, a concept for a new binaural CI stimulation paradigm which implements the SIPI approach is presented. In this paradigm, by applying binaural models of normal hearing, the ITD is extracted from a binaural audio signal. That ITD, combined with the envelope modulation information, defines the positioning of the SIPI pulses. This concept allows enhancing ITD cue precision through binaural processing by integrating reliable ITD information across frequencies or electrodes, respectively. In the contribution, various models and parameters are discussed. Further, strategies on how to avoid conflicts in the across-electrode timing of the SIPI pulses are outlined.

Keywords: Binaural processing, cochlear implants, short inter-pulse intervals

1. INTRODUCTION

Selective hearing refers to the remarkable ability of the human auditory system to decompose a mixture of concurrent sounds, arriving at the two ears, into the original sources and, subsequently, to selectively attend to the desired source while ignoring the others. This is also referred to as the cocktail party problem. While selective hearing is remarkably powerful in normal hearing (NH), it is severely degraded in electric hearing (1), i.e., hearing with cochlear implants (CIs). For speech-in- speech understanding, two important aspects of selective hearing are the segregation of sound sources based on the localization of target and interferers, predominantly based on ITD (2), and the segregation based on monaural features. For speech, one important monaural feature is voice pitch (3), i.e., a talker's fundamental frequency (F0).

In NH, ITD encoded in the rapidly varying temporal fine-structure (AFS) dominates horizontal-plane sound localization for frequencies up to 1.4 kHz whereas above, ITD encoded in the slowly varying temporal envelope and interaural level differences (ILDs) contribute (4). Reliable real-world ITD cues are encoded in the rising portions (i.e., the onset) of the envelope (5).

Both AFS and envelope can encode temporal-pitch cues encoded via phase locking in the auditory-nerve (AN) fibers, yet, AFS-based pitch has been shown to be more salient than envelope-based pitch (6). Oxenham et al. (7) suggested that salient pitch might be encoded by place cues, encoded via the place of the most firing AN sub-populations, rather than AFS cues. However, Graves and Oxenham (8) demonstrated above-chance discrimination of three simultaneous F0s based on the envelope only.

In electric hearing, the spectral resolution is severely limited due to structural limitations of the "system" CI. In particular, the CI electrode array is located in an electrically conductive fluid, the perilymph, with some distance to the AN. To overcome the gap between electrode and AN, current CIs stimulate with rather high electric currents in the range of milliamperes. Due to the perilymph, the electric fields spread and stimulate major parts of the AN. In multi-electrode stimulation, fields of the electrodes interact with each other (9), limiting the number of independent spectral channels to about eight (10), thus being lower than the number of implanted electrodes.

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Electric stimulation of the AN is typically pulsatile rather than continuous. This approach reduces across-electrode interactions (9) and was the major innovation in the first CI stimulation paradigm that provided sufficient spectral precision for good speech understanding (11). Because speech cues (in quiet) are primarily envelope-based, most clinically used stimulation paradigms rely on envelope coding and use “high” pulse rates.

Given their low spectral resolution, CIs rely on precise encoding of temporal cues. Fortunately, CI listeners are rather sensitive to temporal cues (12). A major determinant of a CI’s performance is the stimulation paradigm implemented in the sound processors. The paradigm defines how the acoustic signals arriving at the two ears are converted into electric pulse sequences stimulating the CI listeners’ cochleae. Most clinically used stimulation paradigms provide good to very good speech understanding in quiet, yet, most of them lack precise encoding of ITD and temporal-pitch cues (or sometimes vice versa). Beyond monaural limitations of temporal coding precision, most current stimulation paradigms do not implement binaural processing to improve ITD perception because current sound processors are typically not linked between ears. This results in a further deficit of binaural sensitivity with clinical processors compared to what is possible with highly-controlled experimental research interfaces.

In this contribution, we present the concept of a novel stimulation paradigm that aims to provide precise ITD and temporal-pitch cues (hereafter referred to as timing cues) while *preserving* speech understanding to an extent as currently possible with clinically used stimulation paradigms. First, we briefly summarize timing-cue perception with both direct electrical stimulation via research interfaces and with clinical sound processors while introducing previously developed paradigms that aimed at improved timing-cue perception. Second, we introduce the basic approach on which the paradigm is based on. The approach is derived from recent single-electrode experiments and exploits the use of extra pulses with short inter-pulse intervals (so-called SIPI pulses). Third, we introduce the stimulation paradigm and, finally, outline a concept for binaurally-linked processing and stimulation while assuming that this is someday possible with clinical CI sound processors.

2. TIMING-CUE PERCEPTION IN ELECTRIC HEARING

2.1 Direct Stimulation

When directly stimulating a single interaural electrode pair, sensitivity to ITD encoded in the electric temporal fine-structure (EFS), i.e., the timing of a CI pulse train, degrades for rates exceeding 100 pps (13,14). Even best CI-ITD sensitivity is much worse than best NH-ITD sensitivity (15). Moreover, CI listeners are sensitive to ITD encoded in the temporal envelope of an electric pulse train (14,16), yet, much less than NH listeners (16) and affected by a modulation-rate limitation similar to that found for the EFS pulse rate (14). When multiple interaural electrode pairs are stimulated directly, ITD sensitivity is broadly similar as compared to single pairs (17,18). Mixed-rate approaches, including one electrode with low-rate stimulation in non-apical cochlear regions among four electrodes with high-rate stimulation, yielded low-rate-like sensitivity (19).

Similar to ITD, temporal-pitch perception is severely degraded with CIs compared to NH. Although CI listeners are generally able to perceive temporal pitch, their ability to discriminate EFS-based single-electrode temporal pitch is limited to rates up to around 300 pps (20). The nature of this rate limitation seems to be similar to the rate limitation observed in ITD perception (21), probably both showing a common mechanism. CI listeners are further sensitive to envelope-based pitch if the carrier rate is sufficiently high, with best sensitivity at modulation rates of 100 Hz (22), similar to envelope ITD. For temporal pitch, slight benefits of multi-electrode stimulation compared to single-electrode configurations were found (23,24), yet, those might partly be attributable to increased loudness (24).

2.2 Stimulation with Clinical CI Sound Processors

The stimulation paradigm implemented in a CI sound processor crucially determines a CI listener’s binaural sensitivity. Widely used clinical stimulation paradigms are continuous interleaved sampling [CIS (11)] and the advanced combination encoder [ACE (25)]. Both minimize channel interactions by tightly interleaving the pulses across electrodes. To achieve such a rigorous pulse organization, the AFS is replaced by the EFS in the form of periodic high-rate pulse trains, resulting in envelope coding.

The per-channel EFS rate is typically too high to provide salient EFS-ITD cues. Beyond that, current CI processors operate independently on unsynchronized clocks, which further degrades any residual binaural sensitivity. Still, clinical processors should principally encode envelope ITD with some fidelity. Yet, for speech stimuli, CI listeners’ envelope-ITD sensitivity is rather weak (26).

Clinically used envelope-based stimulation paradigms generally lack low-rate AFS information. Several stimulation strategies that aim to encode the AFS have been proposed, some of which are implemented in newer clinical processors and some have remained experimental. The so-called fine structure processing [FSP (27)] presents AFS information in the EFS of up to three apical electrodes and is also available as a version with four "EFS channels" (FS4) and simultaneous stimulation [FS4-p (28)]. Both peak-derived timing [PDT (29)] and fundamental asynchronous stimulus timing [FAST (30)] lock pulses to envelope peaks, but FAST employs generally lower rates and is thus considered to be a low-rate paradigm. In general, published studies demonstrating significant binaural benefits with those paradigms are lacking (15).

With clinical sound processors, CI listeners also struggle in pitch-related tasks (31,32). Thus, while rather huge across-gender F0 differences might contribute to some extent to CI listeners' selective hearing (33), smaller within-gender differences in F0 likely do not. Previous attempts to improve temporal-pitch coding in stimulation paradigms were based on the explicit enhancement of the per-channel envelope shape. For example, sawtooth (34) or sinusoidal (35) amplitude modulation at full depth was applied. While showing improvements on pitch-related tasks, the effects on speech understanding were so far mixed, showing both degraded (36) as well as preserved (37) performance. Still, none of those approaches is capable of more encoding than one F0 cue concurrently. Consequently, their potential benefit for selective hearing is questionable.

3. INSERTING EXTRA PULSES WITH SHORT INTER-PULSE INTERVALS

There is a trade-off in pulse rate between encoding speech cues (in quiet) and timing cues because envelope-based speech cues require high EFS rates whereas timing cues require low EFS rates.

One approach to improve *single-electrode* ITD sensitivity at rates sufficiently high to encode speech is to apply binaurally coherent jitter to the inter-pulse intervals of the pulse trains (38). This was supported by neurophysiological data, additionally showing that only the randomly generated SIPI pulses in the jittered pulse trains actually caused improved ITD sensitivity (39).

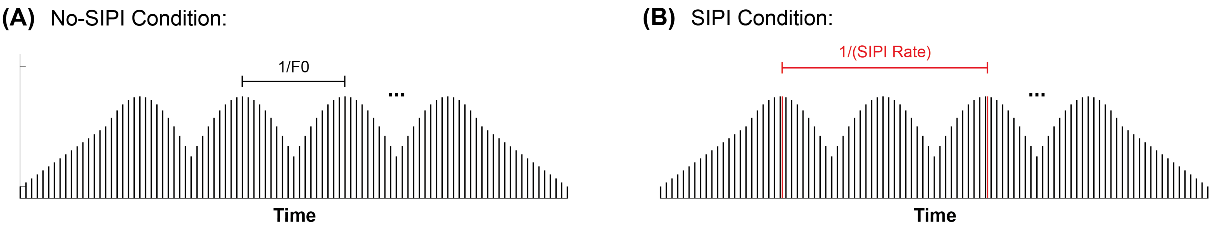

Figure 1 – High-rate single-electrode pulse trains with F0 amplitude modulation. (A) Amplitude modulation only, (B) SIPI pulses inserted at every second envelope peak (SIPI rate is half the F0).

Compared to the jitter approach, a SIPI approach might be better suited for interleaved CIS-like stimulation because it exploits the benefit of the SIPI pulses in a deterministic way. To this end, single-electrode ITD sensitivity was studied with both unmodulated (40) and amplitude-modulated (41) pulse trains. Using unmodulated pulse trains, Srinivasan et al. (40) investigated the effect of the SIPI parameters "rate" (cf. Figure 1B) and "fraction". The SIPI fraction defines the time gap between carrier pulses and SIPI pulses as a portion of the carrier inter-pulse interval. With a 1000-pps carrier, SIPI pulses yielded jitter-like left/right-discrimination performance for SIPI rates up to 200 pps with SIPI fractions up to 10% (40). For those rates and fractions, EFS-like ITD sensitivity was completely restored. The SIPI-pulse effect on ITD sensitivity was also confirmed neurophysiologically (42).

As a next step, the effect of SIPI pulses on single-electrode ITD sensitivity (41) and temporal-pitch sensitivity (43) was studied with high-rate amplitude-modulated pulse trains as shown in Figure 1. In conditions with SIPI pulses placed at envelope peaks (cf. Figure 1B), discrimination performance improved for F0s representing both male and female talkers as compared to conditions without SIPI pulses (cf. Figure 1A). In particular, ITD sensitivity improved at all modulation depths between 0.1 and 0.9, and temporal-pitch sensitivity improved particularly at a modulation depth of 0.1. The data further revealed that the SIPI rate was affected by a limitation similar to that described in Section 2.

The above-described effects of the SIPI pulses highlight the fact that the stimulation paradigm proposed in this contribution cannot consider binaural hearing in isolation without controlling for monaural effects on temporal pitch.

4. STIMULATION PARADIGM

4.1 General Concept

Figure 2 shows the flow chart of the proposed stimulation paradigm. It will provide precise encoding of timing cues in addition to speech understanding by combining 1) low-rate AFS encoded via EFS at the two most apical electrodes [“EFS channels”, cf. FSP (27)], 2) high-rate envelope coding [“ENV channels”, cf. CIS (11)], 3) superimposed with SIPI pulses (40,41,43) up to the most basal channels, and 4) interaurally-linked, binaural signal processing employing models of acoustic binaural hearing.

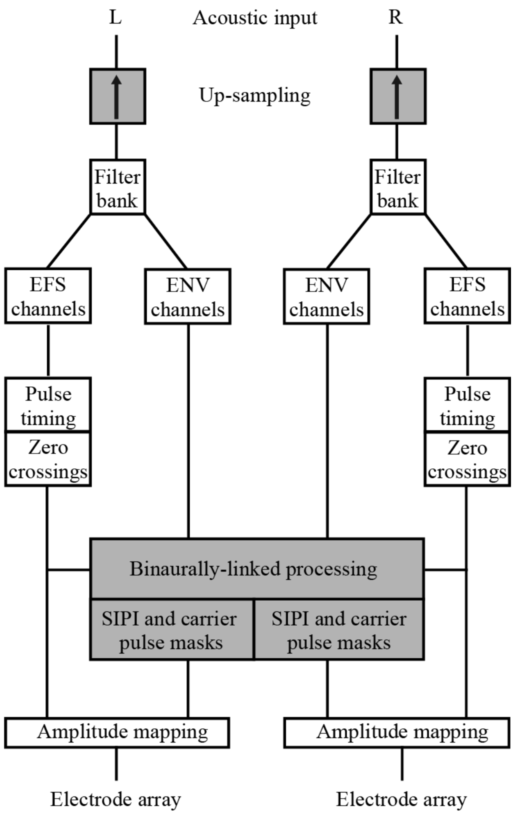

Figure 2 – Flow chart of the MissiSIPI stimulation paradigm. Steps relevant for binaural sensitivity in grey.

Compared to previous approaches, innovations concern the steps (c) and (d). In the end, the stimulation paradigm will generate Multi-channel, interaurally-linked stimulation sequences incorporating SIPI pulses, hereafter referred to as *MissiSIPI*.

The following processing steps are planned:

1. *Up-sampling* of the acoustic signals to enhance MissiSIPI’s temporal precision.
2. Bandpass *filter banks* split the signal into twelve bands within short time windows. The filter bandwidths and thus MissiSIPI’s frequency range orientate on FSP/FS4 (28).
3. For the *EFS channels*, envelope and phase of the analytic signal, required for pulse timing, are extracted. Pulses of the EFS are triggered by positive zero crossings and the amplitudes of those pulses are determined by the envelope. EFS channels are not further processed prior to amplitude mapping. Timing cues are encoded implicitly.
4. For the *ENV channels*, envelope-peak timing is extracted per channel. The extraction method is derived from statistical timing analysis of per-band signals of English [TIMIT corpus (44)] and German [Kiel corpus (45)] speech signals of both male and female talkers.
5. *Binaurally-linked processing* can be activated to enhance binaural sensitivity. When active, per interaural channel, envelope ITDs are estimated from the left and right-ear envelope-peak vectors. If the ITDs are unreliable, more reliable EFS-channel ITDs are used to refine the envelope ITDs. More details on binaural processing are provided in Section 4.2.
6. *SIPI and carrier-pulse masks:* Each window is classified to be either voiced or unvoiced (46). Because the SIPI approach affects pitch perception due to its repetitive manner, SIPI pulses

are only inserted in voiced windows. In those windows, SIPI-pulse pairs are placed at time instances of (refined) envelope-peak vectors. The so-called "F0-coding option", when activated, implicitly defines the SIPI rate by classifying envelope peaks as corresponding to the F0 in the current window. The SIPI fraction remains adjustable within a certain (low-value) range. ENV-channel carrier pulse masks, filling time instances with neither a SIPI-pulse pair nor an EFS-channel pulse are generated, aiming for uniform envelope sampling and a target carrier rate of 1000 pps per channel.

7. *Amplitude mapping:* A logarithmic map-law is applied. The per-channel pulse vectors are transformed into biphasic pulse sequences and sent to the CI electrode arrays.

In this early stage of development, our main goal is to provide high binaural sensitivity without considering the limitations of current CI sound processors. Hence, MissiSIPI will be developed for direct stimulation with a laboratory research interface such as the Research Interface Box II (RIB2).

Compared to existing stimulation paradigms aiming at improved ITD perception, we expect advantages of MissiSIPI because 1) it provides timing cues across the entire CI electrode array, 2) timing cues are provided at rates below the rate limitations and should, thus, be salient, and 3) it still uses high-rate "speech-friendly" stimulation on all-but-two available electrodes.

Compared to existing stimulation paradigms aiming at improved temporal-pitch perception, we expect advantages of MissiSIPI because 1) we aim for preservation of spectral cues and 2) we assume sufficient temporal flexibility of the multi-electrode SIPI approach to encode F0 (and ITD) cues of more than one source.

4.2 Binaural Processing

The NH auditory system is exceptionally good at localizing concurrently active sound sources while suppressing interferences such as reflections. It does so by evaluating AFS information only during the rising portion of each envelope cycle where ITD is least affected by reverberation (5). Yet, in electric hearing, ITD is most saliently encoded at envelope peaks (41,47).

Motivated by the Jeffress model for neural ITD coding which consists of several coincidence detectors optimized for a certain interaural delay, interaural cross-correlation (ICC) is often used to estimate the direction of arrival of a sound source (48). Yet, ICC alone does not take into account the reliability of an ITD estimate, which in turn could lead to undetected errors.

One elegant way to consider the reliability is to also use the ICC estimate as an indicator of its own reliability. Faller and Merimaa (49) proposed to use short-term integration of the interaural coherence (IC), i.e., the maximum of the ICC, to label time instances as reliable or not in case the IC exceeds a certain threshold. In addition to only having to perform one computation for both ITD and IC, NH listeners seems to be exceptionally sensitivity to changes in IC (50).

For MissiSIPI, the results from Dietz et al. (5) will be considered to identify reliable per-electrode timing events to place SIPI pulses. In addition to that, the use of SIPI pulses will depend on the per-electrode IC to avoid erroneous SIPI-ITD cues. In case only some electrode signals have a high IC, reliable ITD estimates can be integrated across electrodes to improve binaural sensitivity by providing reliable and salient ITD cues across the entire CI electrode array. In particular, given that low-rate ITD is perceived most saliently, reliable EFS-ITD estimates as determined by IC will be used to refine the envelope ITD in non-apical channels. Yet, the effects of some important parameters of this method still have to be evaluated to parameterize MissiSIPI for arbitrary acoustic signals.

4.3 Conflicts in Across-Electrode Timing

With arbitrary acoustic inputs from arbitrary azimuthal locations simultaneous SIPI stimulation across electrodes is likely to be demanded occasionally. Because MissiSIPI will employ interleaved stimulation across electrodes, routines to solve such pulse conflicts have to be implemented.

Currently, three candidates seem to be most promising. First, parallel stimulation resolves als conflicts, however, it will result in severe electric-field interactions (9). Thus, conditions that apply parallel stimulation have to be carefully selected. Second, individual SIPI pulses can be removed. A recent study by Egger et al. (51) could aid in determining the maximum amount of (interaurally uncoordinated) pulse removal. Assuming similar ITD sensitivity with low-rate EFS stimulation and high-rate SIPI stimulation (40), up to about 8% of pulses could be removed without significantly degrading ITD sensitivity (51). Third, conflicting pulses could occasionally be delayed, resulting in a form of jitter of the SIPI rate with potential consequences on pitch sensitivity.

All routines will consider a trade-off between ITD and pitch coding, with ITD coding having priority because of higher binaural than monaural timing sensitivity.

5. SUMMARY

Current CI stimulation paradigms lack precise encoding of timing cues *in addition to* speech cues because a pulse-rate trade-off specific to electric hearing remains unsolved. A single-electrode approach, relying on the insertion of SIPI pulses, has been shown to enhance timing cues. A novel stimulation paradigm (MissiSIPI) was proposed, employing a multi-electrode SIPI approach for non-apical electrodes with CIS-like stimulation (ENV channels) while using FSP-like stimulation at apical electrodes. The paradigm uses models of binaural hearing in an interaurally-linked processing stage to refine envelope-ITD encoding by combining reliable ITD information across electrodes.

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