INTERSPEECH 2023
20-24 August 2023, Dublin, Ireland

F0inTFS: A lightweight periodicity enhancement strategy for cochlear implants

Huali Zhou[1], *Fanhui Kong*[1], *Nengheng Zheng*[1], *Qinglin Meng*[2]

[1] Guangdong Key Laboratory of Intelligent Information Processing,
College of Electronics and Information Engineering, Shenzhen University, Shenzhen, China
[2]Acoustics Laboratory, School of Physics and Optoelectronics,
South China University of Technology, Guangzhou, China

nhzheng@szu.edu.cn, mengqinglin@scut.edu.cn

Abstract

Periodicity is one of the main cues for pitch-related speech perception but is poorly encoded in cochlear implants (CIs). Most efforts towards CI periodicity enhancement involve explicit fundamental frequency (F0) detection, which requires additional computational loads and may not be reliable in real settings. Here we propose a new strategy, namely F0inTFS, which encodes F0 information without explicit F0 detection. Our idea is inspired by the fact that temporal fine structures (TFS) at the low-frequency channels inherently contain strong F0-related periodicity cues. In F0inTFS, the TFS of the lowest-frequency channel is integrated into the temporal envelopes at all higher-frequency channels using a specifically designed algorithm. F0inTFS can be lightly implemented in the FFT-based framework of one clinically used strategy, i.e., the Advanced Combination Encoder (ACE) strategy. The benefits of F0inTFS are supported by a lexical tone perception experiment in simulated CI users.

Index Terms: speech recognition, cochlear implant, coding strategy, lexical tone perception

1. Introduction

Cochlear implants (CIs) have successfully restored hearing to more than one million deaf people worldwide [1]. Yet there's still a long way to go before CIs' performance is comparable to that of the normal hearing system, for example in the aspect of pitch perception. Pitch is one of the primary auditory sensations and plays an important role in the perception of music, auditory stream segregation, intonation, and lexical tone in tonal languages. In the normal-hearing auditory system, pitch can be conveyed by the tonotopic place of stimulation along the cochlea (the place cue), and by the temporal periodicity at a given place of stimulation [2, 3]. This study was concerned with the encoding of periodicity and its effects on Mandarin tone perception in CIs.

Periodicity is poorly encoded in CIs. In the normal hearing auditory system, the fundamental frequency (F0) of a harmonic complex sound can be derived by combining the temporal fine structure (the rapidly changing carrier) of low-numbered harmonics resolved by auditory filters. A less salient cue is the F0 information encoded via the envelope (the slowly changing amplitude) repetition rate of the outputs of the auditory filters that contain groups of unresolved higher harmonics [2]. In current CIs, acoustic signals are divided into several frequency bands and information is encoded into the electrical pulses generated by electrodes located along the basilar membrane of the cochlear. The Continuous Interleaved Sampling (CIS) strategy, a typical sound coding strategy broadly implemented in many CIs, transmits the temporal envelope of the acoustic signal, whereas the temporal fine structure is discarded. As a consequence, periodicity encoding in CIs is restricted to the less salient temporal envelope cues.

Numerous efforts have been made toward enhancing periodicity encoding in CIs. The Fine Structure Processing (FSP) and its variant FS4 strategies use an explicit way of enhancing the periodicity in the pulse rates [4, 5]. Electrical pulses are triggered at each zero crossing of acoustic signals in the low-frequency channels, resulting in pulse rates varying with the temporal fine structures in these channels. However, mixed results have been reported with these strategies [6, 7]. Another line of research tried to make use of envelope modulations for fixed-rate pulse trains. Geurts and Wouters (2001) increased the modulation depth of F0-related envelope modulations in the channel outputs of the CIS strategy and found no significant benefit in pitch perception [8]. Their study also suggested the importance of synchronous fluctuations across channels for periodicity encoding. Green *et al*. (2004) used a sharpened sawtooth waveform with a periodicity identical to the input stimuli to amplitude modulate the channels in the CIS strategy, and found a small but significant advantage in pitch perception [9]. Vandali *et al.* (2005) also observed better performance with algorithms that provided deeper F0-related modulations synchronized across all channels, including the multichannel envelope modulation (MEM) strategy [10]. The F0mod strategy [11] and the Optimized Pitch and Language (OPAL) strategy [12] apply additional amplitude modulation at the envelopes of each electrode with a modulation rate of F0. Both strategies have been extensively evaluated in a set of experiments with benefits in pitch perception and no effect on speech recognition [13, 14, 15, 16, 17, 18]. More recently, Lindenbeck *et al.* have explored inserting extra pulses with short interpulse intervals (SIPI) at the rate of F0 to enhance the periodicity, and improved pitch sensitivity was observed in a preliminary single-electrode experiment [19].

Most of these methods involve explicit extraction of F0 from the acoustic input (a timing and energy detector is involved in FSP and FS4 to extract the zero-crossings and envelopes), which require additional computational loads and may not be reliable in real settings. In this paper, we propose a new periodicity enhancement algorithm, F0inTFS, which implicitly encodes F0 information without explicit F0 detection. It can be lightly implemented in clinically used strategies. The detailed algorithm is described in Section 2, and its performance is evaluated in an experiment with simulated CIs in Section 3. F0inTFS is by no means a perfect one but one that is lightweight and easy to implement for real-time use.

 10.21437/Interspeech.2023-652

2. The Proposed Method

2.1. Rationale

The idea of F0inTFS is inspired by the fact that temporal fine structures (TFS) at low-frequency channels inherently contain strong F0-related periodicity cues. However, these F0-related periodicity cues are discarded during the envelope extraction process in most clinical CI strategies, e.g., the Advanced Combination Encoder (ACE) strategy (the default strategy in Cochlear devices).

An overview of the processing blocks of the proposed method (F0inTFS) is depicted in Fig.1(a). In this paper, F0inTFS is based on the ACE strategy and incorporates additional modulation to the channel envelopes of the ACE strategy. Actually, it is also suitable for other strategies. For the lowest-frequency channel, F0inTFS does not use the envelope for stimulation. Instead, the output of the bandpass filter for that channel is used for stimulation and to apply modulations to envelopes of all higher channels, as shown in the dashed rectangle in Fig.1(a).

2.2. Implementations

This section presents an FFT-based real-time implementation of the F0inTFS strategies and the ACE strategy for comparison. This real-time implementation makes possible a direct comparison of performance in real CI users between both strategies in the future.

Figure 1(b) and (c) show the FFT-based implementations for ACE and F0inTFS, respectively. The bandpass filterbank is implemented by an FFT and then grouping specified FFT bins into a number of frequency channels (typically equal to the number, the default number of 22 is shown here). ACE extracts the envelope of each channel by calculating the root of a summation of bin powers (Fig. 1(b)). A subset of channels with the highest signal levels (spectral maxima) is selected, and corresponding electrodes are then stimulated with pulse intensities derived from logarithmic compression and acoustic-electric mapping.

To keep the place cue consistent with that of ACE, F0inTFS use the same maxima selection process as in ACE, i.e., based on channel envelopes. Consequently, F0inTFS stimulates the same electrodes as ACE does. After maxima selection, F0inTFS has an additional amplitude modulation process. The selected channel envelopes are further amplitude modulated with a modulator derived from the first (lowest-frequency) channel by Eq. (1) as shown in Fig. 1(c). To preserve the TFS (hence the F0 periodicity) in the first channel (lowest frequency), the real part of the third FFT bin is derived and used as the TFS in this channel. If the first channel is selected in the maxima selection process, the rectified TFS is used as the signal for this channel.

$$M_n = 0.5(1 + \frac{a}{b})E_n, \quad 2 \leq n \leq 22 \tag{1}$$

where E_n denotes the envelope of the n^{th} channel, a represents the TFS in the first channel (calculated as $Re(X_3)$), b is the envelope in the first channel (calculated as $|X_3|$, X_3 refers to the third FFT bin and M_n is the modulated envelope at the n^{th} channel.

To show the difference in electric stimulation of the two strategies, Figs. 1 (d) and (e) show the electrical stimulation patterns (electrodograms; 1800 pulses per second (pps)) recorded using a 5-harmonic complex tone with 250-Hz F0 and 10-dB spectral roll-off. In the electrodograms, a vertical bar denotes an electrical pulse and is plotted at the time and electrode position of the electrical pulse. The height of the vertical bar represents the stimulus level. There's limited periodicity in stimulation patterns of ACE, as most channel envelopes are flat or with shallow modulation depth. In contrast, enhanced periodicity is observed in F0inTFS. Deep modulations are observed in each channel, and the modulations are synchronous across channels. The enhanced periodicity in F0inTFS may contribute to better pitch perception, which is tested in the experiment presented in the next section.

3. Experiment

3.1. Study design

A subjective experiment was carried out to see whether the theoretically enhanced periodicity in the proposed strategy translates into any benefits in pitch perception. A lexical tone perception task was used as a measure of pitch perception. In tonal languages, the tonality of syllables conveys lexical meaning. Mandarin has four lexical tones, defined by the pitch contour of the syllable, namely, Tone 1: flat and high, Tone 2: rising, Tone 3: falling and then rising, and Tone 4: falling. This experiment compares the perception of lexical tones (pitch contours) when using the proposed F0inTFS strategy. As a first step, vocoder simulations in normal-hearing listeners were used in this experiment. First, speech materials were processed using a vocoder to simulate the sound received by CI users with both strategies. Then, a group of normal-hearing listeners was tested using the processed materials. Percent correct scores of each strategy were calculated and compared.

3.2. Methods

3.2.1. Materials

Disyllabic words from a Mandarin-tone corpus [20] designed to highlight the use of pitch cue in lexical tone perception were used. In natural speech, besides pitch contour as the primary cue for lexical tone perception, there are also some secondary cues such as the loudness contour and duration [20, 21, 22, 23]. In the corpus used in this study, the effects of the secondary cues are eliminated by manipulating the loudness and pitch contour of the syllables. The ability to use pitch cues for lexical tone recognition could be reflected by the scores in a tone identification task using this corpus.

3.2.2. Signal processing

The speech materials were processed using an adapted sine-wave vocoder [24] to simulate CIs. Vocoders are commonly used as a simulation tool to help researchers evaluate how the auditory system processes degraded sounds under controlled conditions [25]. Sine-wave vocoders extract envelopes in several frequency channels of the speech signal and then modulate them with a set of sinusoidal carriers to simulate tonotopic stimulation in CIs. However, this process simulates only the envelope extraction process in CIs, while the following maxima selection, compression, and mapping process are not simulated [26]. In this study, the sine-wave vocoder was adapted to simulate the complete CI sound process chain by deriving the envelopes from the electrodogram data, which involves not only envelope extraction but also the maxima selection, compression, and mapping process.

Specifically, the envelopes were derived using the following steps. First, the pulse sequence in the electrodogram (in

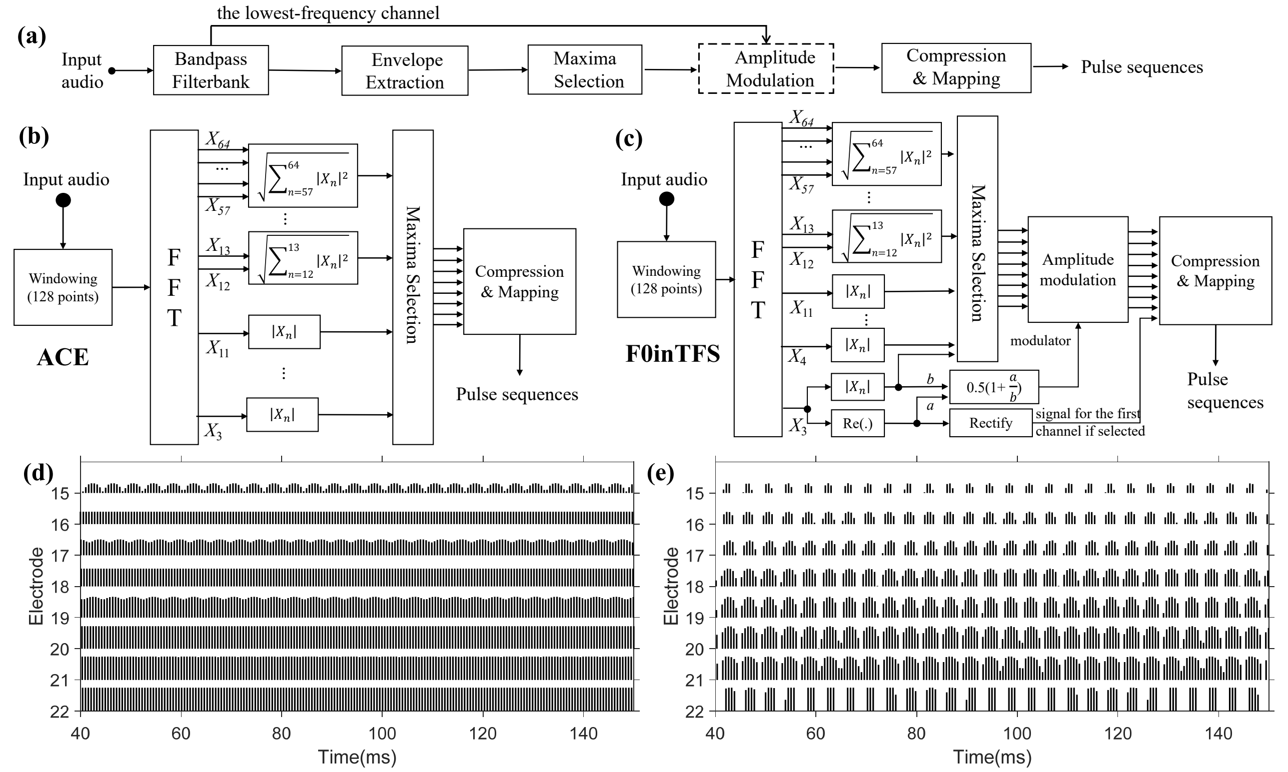

Figure 1: *Block diagram and FFT implementations. (a): block diagram of F0inTFS showing the signal path from input audio signal to pulse sequences. The dashed rectangle shows the additional processing to ACE. (b) & (c): FFT implementations of the ACE and F0inTFS strategies, respectively. (d) & (e): electrical stimulation patterns (electrodogram) for a synthetic 5-harmonic complex tone processed by ACE and F0inTFS, respectively.*

which each pulse was represented with a biphasic cathodic leading pulse) for a particular channel was up-sampled at a high sampling frequency of 10^6 Hz. Then an empirical envelope estimation algorithm [27] was used to extract the envelope with a cut-off frequency of 400 Hz. The extracted envelope was then downsampled to the sampling frequency (16 kHz) of the time carriers and used to modulate the carrier. The lower sideband after modulation was removed to avoid confusion caused by inconsistent changes between two sidebands, which is a problem that does not exist in CI electric hearing.

Two strategies were simulated, namely, the proposed F0inTFS strategy, and the ACE strategy as the baseline. The implementation of the ACE strategy in the CCi-Mobile research interface was used ([28, 29]). Specifically, a sampling rate of 16 kHz, an FFT length of 128, a hanning window, and a frame size of 128 was used. The F0inTFS strategy was lightly implemented within the framework of the ACE strategy with the differences described in Section 2. The electric threshold value was set to 100 CL, and the maximum comfortable level to 150 CL, to simulate a clinically typical electric dynamic range of 50 CL. Two pulse rates were used, 900 pps and 1800 pps, to simulate the default pulse rate in ACE, and a higher pulse rate for better envelope representation, respectively.

3.2.3. Procedures

Six normal-hearing listeners (three females) participated in the experiment. They were tested in a quiet room and used headphones to deliver sound at a comfortable and loud enough level. A three-alternative forced-choice (3AFC) paradigm was used. Each time a word was presented, listeners responded by picking the perceived tone from a set of options displayed on the screen. The option set consisted of three words with the same consonant and vowel but differed in tone. No feedback about the correctness of the response was provided during testing. Before formal tests, a training session with feedback was conducted to familiarize listeners with the sound of the vocoder.

The test corpus consists of 270 words, among which 90 were used for training and the remaining 180 for tests. Each word was processed with both the F0inTFS and ACE strategy with a pulse rate of 900 and 1800 pps, resulting in 4 versions for each word. Each listener was tested with 720 tokens (180 words $\times$ 4 versions/word) after a training session of 360 tokens (90 words $\times$ 4 versions/word). The order of tokens and versions was randomized across listeners.

3.3. Results

A two-way repeated-measures analysis of variance (rm-ANOVA) was conducted with strategy (ACE vs. F0inTFS) and pulse rate (900 pps vs. 1800 pps) as independent variables and percent correct score as the dependent variable. A significant main effect of strategy ($F(1,5) = 44.73, p = 0.001$) was observed, but not for pulse rate ($F(1,5) = 0.57, p = 0.484$), not the interaction between strategy and pulse rate ($F(1,5) = 1.49, p = 0.277$). As there was no significant effect of the pulse rate, the results of the two pulse rates were pooled together to show the difference between strategies as depicted in Fig. 2. All participants had higher scores (better performance) with the F0inTFS strategy than with the ACE strat-

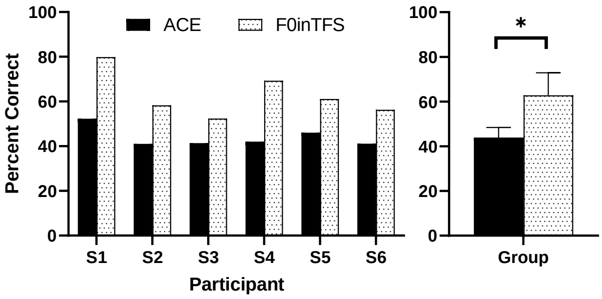

Figure 2: *Lexical tone perception results with simulated CIs. The asterisk indicates the statistical significance.*

egy. The group mean percent correct score was 44.0% for the ACE strategy and 62.9% for the F0inTFS strategy. F0inTFS had an improvement of 18.9%, which is statistically significant ($t(11) = 8.864, p < 0.001$, a paired-sample t test).

4. Discussions

4.1. Main findings

This study proposes a new sound coding strategy aimed at enhancing periodicity in CIs. Preliminary results of a lexical-tone perception experiment using vocoder simulations were presented. A significant improvement of 18.9 percentage points in Mandarin lexical tone recognition was obtained using vocoder simulations of the F0inTFS strategy compared to the baseline ACE strategy. This outcome suggests that F0inTFS provides more salient pitch cues for lexical tone perception. In F0inTFS, the maxima selection process is also based on the summed-power envelopes as in ACE, thus both strategies provide similar place cues. Therefore, the more salient pitch cues can be attributed to the enhanced temporal periodicity in the envelopes of the F0inTFS strategy.

4.2. Comparions with the literature

These findings are consistent with those of related studies examining Mandarin lexical tone perception using the F0mod strategy [14] and the OPAL strategy [17]. Both strategies in those previous studies also showed a significant benefit for lexical tone perception. Although different materials make it impossible to compare the experiment results directly, the combined findings of the present study and the studies in [14] and [17] suggest that the enhanced periodicity cues via additional amplitude modulations in channel envelopes of ACE can improve lexical tone perception.

A notable difference between F0inTFS and F0mod or OPAL is that the F0 information is derived using explicit F0 extractors in those strategies, whereas F0inTFS uses the F0 information inherently contained in the TFS of the lowest-frequency channel, which makes F0inTFS much more lightweight than those strategies. The improvement observed in this study suggests that the F0 information inherently contained in the TFS of the lowest-frequency channel can be used to enhance the temporal periodicity of the envelopes, which in turn provides more salient pitch cues for lexical tone perception.

Another related strategy is the MEM strategy [10] which used the envelope of the broadband signal to modulate the channel envelopes of the ACE strategy. The envelope of the broadband signal also inherently contains some periodicity information for F0. However, no significant benefit to lexical tone perception or sentence perception was observed compared to ACE in a group of Cantonese-speaking adult CI users [30, 31]. A major difference between F0inTFS and MEM is the source of F0 information, which could result in different degrees of salience of F0 cues and different computational costs. F0 information is lightly derived from the TFS of the lowest-frequency channel in F0inTFS, but for MEM it is from the envelope of the broadband signal via an extra envelope extractor. It is possible that the envelope of the broadband signal provides less salient F0 cues, as it may contain complex interactions among many components.

4.3. Limitations

There are several limitations to this study. First, the speech intelligibility was not tested. As our main goal is to enhance periodicity, we start by testing lexical tone perception which is a pitch-related speech perception task in this study. Previous studies have shown that similar modulation schemes have no detrimental effect on overall speech intelligibility (see reference [12, 14]). Second, since the experiment was performed using vocoder simulations, it is yet to be investigated whether the observed improvement could translate to actual CI listeners. Our specifically designed vocoder faithfully replicated all signal processing stages in the CI sound processing chain. It transmits information similar to that in an actual CI. Ultimately, verification in actual CI listeners is necessary.

A potential limitation of F0inTFS is the effective F0 range it works in. F0inTFS relies on the F0 information within the frequency range of the first channel (up to approximately 300 Hz), which spans the typical F0 range of speech. For some speech with higher F0s, the F0 information in the first channel might be weak. Although the range could be extended to some extent by combining one more FFT bin into the first channel, the temporal pitch limits in electric hearing make pitch perception extremely difficult for F0s of 300 Hz or higher. Limitations of performance for F0s near 300 Hz were observed for previous strategies using a similar approach of additional amplitude modulation [14]. Other techniques (e.g., by frequency downshfiting [32, 17]) might be necessary for improving pitch perception with F0s near 300 Hz or higher.

5. CONCLUSIONS

A new sound coding strategy, F0inTFS, is proposed to enhance periodicity encoding in CIs. F0inTFS is lightly implemented by modulating the multiband envelopes by the F0-related lowest band signal. Instead of explicit F0 extraction, F0inTFS derives F0 information implicitly from the TFS of the lowest-frequency band. Periodicity is enhanced in F0inTFS by the deep modulations with the frequency of F0 and synchronous across channels, which is supported by a Mandarin tone identification experiment in simulated CI listeners.

6. Acknowledgments

We thank all participants for their participation in the experiment. This work was supported by the Guangdong Basic and Applied Basic Research Foundation Grant (2022A1515011361) and the Shenzhen Fundamental Research Program (20220809191805001). Nengheng Zheng and Qinglin Meng are the corresponding authors.

7. References

[1] F.-G. Zeng, "Celebrating the one millionth cochlear implant," *JASA Express Letters*, vol. 2, no. 7, p. 077201, 2022.

[2] A. J. Oxenham, "Pitch perception," *Journal of Neuroscience*, vol. 32, no. 39, pp. 13 335–13 338, 2012.

[3] B. C. Moore, *An introduction to the psychology of hearing*. Brill, 2012.

[4] C. M. Zierhofer, "Electrical nerve stimulation based on channel specific sampling sequences," Jul. 15 2003, uS Patent 6,594,525.

[5] I. Hochmair, P. Nopp, C. Jolly, M. Schmidt, H. Schößer, C. Garnham, and I. Anderson, "Med-el cochlear implants: state of the art and a glimpse into the future," *Trends in amplification*, vol. 10, no. 4, pp. 201–219, 2006.

[6] L. Magnusson, "Comparison of the fine structure processing (fsp) strategy and the cis strategy used in the med-el cochlear implant system: speech intelligibility and music sound quality," *International Journal of Audiology*, vol. 50, no. 4, pp. 279–287, 2011.

[7] M. T. Dillon, E. Buss, E. R. King, E. J. Deres, S. N. Obarowski, M. L. Anderson, and M. C. Adunka, "Comparison of two cochlear implant coding strategies on speech perception," *Cochlear implants international*, vol. 17, no. 6, pp. 263–270, 2016.

[8] L. Geurts and J. Wouters, "Coding of the fundamental frequency in continuous interleaved sampling processors for cochlear implants," *The Journal of the Acoustical Society of America*, vol. 109, no. 2, pp. 713–726, 2001.

[9] T. Green, A. Faulkner, and S. Rosen, "Enhancing temporal cues to voice pitch in continuous interleaved sampling cochlear implants," *The Journal of the Acoustical Society of America*, vol. 116, no. 4, pp. 2298–2310, 2004.

[10] A. E. Vandali, C. Sucher, D. J. Tsang, C. M. McKay, J. W. Chew, and H. J. McDermott, "Pitch ranking ability of cochlear implant recipients: A comparison of sound-processing strategies," *The Journal of the Acoustical Society of America*, vol. 117, no. 5, pp. 3126–3138, 2005.

[11] J. Laneau, J. Wouters, and M. Moonen, "Improved music perception with explicit pitch coding in cochlear implants," *Audiology and Neurotology*, vol. 11, no. 1, pp. 38–52, 2006.

[12] A. E. Vandali and R. J. van Hoesel, "Development of a temporal fundamental frequency coding strategy for cochlear implants," *The Journal of the Acoustical Society of America*, vol. 129, no. 6, pp. 4023–4036, 2011.

[13] M. Milczynski, J. Wouters, and A. Van Wieringen, "Improved fundamental frequency coding in cochlear implant signal processing," *The Journal of the Acoustical Society of America*, vol. 125, no. 4, pp. 2260–2271, 2009.

[14] M. Milczynski, J. E. Chang, J. Wouters, and A. Van Wieringen, "Perception of mandarin chinese with cochlear implants using enhanced temporal pitch cues," *Hearing Research*, vol. 285, no. 1-2, pp. 1–12, 2012.

[15] T. Francart, A. Osses, and J. Wouters, "Speech perception with f0mod, a cochlear implant pitch coding strategy," *International journal of audiology*, vol. 54, no. 6, pp. 424–432, 2015.

[16] A. E. Vandali and R. J. van Hoesel, "Enhancement of temporal cues to pitch in cochlear implants: Effects on pitch ranking," *The Journal of the Acoustical Society of America*, vol. 132, no. 1, pp. 392–402, 2012.

[17] A. E. Vandali, P. W. Dawson, and K. Arora, "Results using the opal strategy in mandarin speaking cochlear implant recipients," *International Journal of Audiology*, vol. 56, no. sup2, pp. S74–S85, 2017.

[18] A. Vandali, P. Dawson, A. Au, Y. Yu, M. Brown, M. Goorevich, and R. Cowan, "Evaluation of the optimized pitch and language strategy in cochlear implant recipients," *Ear and Hearing*, vol. 40, no. 3, pp. 555–567, 2019.

[19] M. J. Lindenbeck, B. Laback, P. Majdak, and S. Srinivasan, "Temporal-pitch sensitivity in electric hearing with amplitude modulation and inserted pulses with short inter-pulse intervals," *The Journal of the Acoustical Society of America*, vol. 147, no. 2, pp. 777–793, 2020.

[20] X. Wang, Y. Mo, F. Kong, W. Guo, H. Zhou, N. Zheng, J. W. H. Schnupp, Y. Zheng, and Q. Meng, "Cochlear-implant mandarin tone recognition with a disyllabic word corpus," *Frontiers in Psychology*, vol. 47, no. 1, pp. 1–12, 2022.

[21] L. Xu, Y. Tsai, and B. E. Pfingst, "Features of stimulation affecting tonal-speech perception: Implications for cochlear prostheses," *The Journal of the Acoustical Society of America*, vol. 112, no. 1, pp. 247–258, 2002.

[22] Y.-Y. Kong and F.-G. Zeng, "Temporal and spectral cues in mandarin tone recognition," *The Journal of the Acoustical Society of America*, vol. 120, no. 5, pp. 2830–2840, 2006.

[23] Q. Meng, N. Zheng, and X. Li, "Loudness contour can influence mandarin tone recognition: Vocoder simulation and cochlear implants," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 6, pp. 641–649, 2017.

[24] M. F. Dorman, P. C. Loizou, and D. Rainey, "Speech intelligibility as a function of the number of channels of stimulation for signal processors using sine-wave and noise-band outputs," *The Journal of the Acoustical Society of America*, vol. 102, no. 4, pp. 2403–2411, 1997.

[25] R. V. Shannon, F.-G. Zeng, V. Kamath, J. Wygonski, and M. Ekelid, "Speech recognition with primarily temporal cues," *Science*, vol. 270, no. 5234, pp. 303–304, 1995.

[26] Q. Meng, H. Zhou, T. Lu, and F.-G. Zeng, "Pulsatile gaussian-enveloped tones (get) for cochlear-implant simulation," *Applied Acoustics*, vol. 208, p. 109386, 2023.

[27] Q. Meng, M. Yuan, Z. Yang, and H. Feng, "An empirical envelope estimation algorithm," in *2013 6th International Congress on Image and Signal Processing (CISP)*, vol. 2. IEEE, 2013, pp. 1132–1136.

[28] R. Ghosh, H. Ali, and J. H. Hansen, "Cci-mobile: A portable real time speech processing platform for cochlear implant and hearing research," *IEEE Transactions on Biomedical Engineering*, vol. 69, no. 3, pp. 1251–1263, 2021.

[29] A. Kan and Q. Meng, "The temporal limits encoder as a sound coding strategy for bilateral cochlear implants," *IEEE/ACM transactions on audio, speech, and language processing*, vol. 29, pp. 265–273, 2020.

[30] V. Ciocca, A. Vandali, L. Wong, B. Luk, and I. V.W.K., "Pitch perception by cochlear implant users. oral presentation," *Fifth Asia Pacific Symposium on Cochlear Implant and Related Sciences, Hong Kong, 26-28 Nov.*, 2005.

[31] L. L. Wong, A. E. Vandali, V. Ciocca, B. Luk, V. W. Ip, B. Murray, H. C. Yu, and I. Chung, "New cochlear implant coding strategy for tonal language speakers," *International journal of audiology*, vol. 47, no. 6, pp. 337–347, 2008.

[32] H. Zhou, A. Kan, G. Yu, Z. Guo, N. Zheng, and Q. Meng, "Pitch perception with the temporal limits encoder for cochlear implants," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 30, pp. 2528–2539, 2022.