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Simulated Phase-Locking Stimulation: An Improved Speech Processing Strategy for Cochlear Implants

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Key Words
Speech processing strateg · Cochlear implant · Phase information · Chinese speech

Abstract
The continuous interleaved sampling (CIS) speech-process-

Introduction

Cochlear implant (CI) devices have been applied successfull to help profoundl deaf patients achieve hearing through electrical stimulation of the auditor nerve with fine electrodes inserted into the scala t mpani of the cochlea [1]. The performance of listeners using CI devices depends largel on the signal processor transforming speech signals to electrical stimuli. Several signal-processing techniques have been developed over the past 30 ears, and have been classified into 2 major t pes: waveform representation and feature e traction. As a t pical waveform representation approach, the continuous interleaved sampling (CIS) strateg developed b researchers at the Research Triangle Institute shows a high level of speech recognition for the CI users speaking monotonal languages, such as English and German [2 4].

However, it has been reported that CI users who speak Chinese have poor identification of vowels and consonants [5, 6]. Chinese is a tonal language, which has 4 tonal patterns as defined b the fundamental frequenc (F0) of voiced speech. For e ample, changing the tone in the s llable 'ma' from flat to rising, or to falling and rising, or to falling, changes the meaning of the word. Using the CIS strateg , Xu et al. [7] studied how signal-processing parameters, such as the low-pass cutoff frequenc for

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e tracting amplitude envelopes and the number of channels of the band-pass filter bank, affect tonal recognition. The results of their studies show that recognition of the 4 Mandarin tonal patterns depends on both the number of channels and the low-pass cutoff frequenc , and temporal cues can compensate for diminished spectral cues in tone recognition and vice versa. In addition, the importance of pitch and periodicit information in Chinese speech recognition have also been confirmed in the stud b Fu et al. [8], in which 3 carrier band conditions were tested, including noise-band carrier for all speech segments, pulse train carriers for the voiced speech segment whose rate followed the F0 of the speech signals, and fi ed-rate pulse train carriers for voiced speech segments. The results show that the F0-controlled pulse train carriers produce the best performance, indicating the need to provide adequate amounts of both pitch and periodicit information to Chinese-speaking CI patients.

Although some CI users perform well in speech recognition as normal listeners in a quiet environment, the have considerable difficulties in performance when maskers, especiall fluctuating maskers, are presented [9]. F0 information has long been thought to pla an important role in perceptuall segregating sound sources [10]. A reduction in F0 cues produced b cochlear-implant processing leads to difficult in segregating different sources. Moreover, fine structure information is also important for sound locali ation and pitch perception [11]. So, it is important to stud how to conve more fine structure information of the speech signal to CI users.

Although in some CI strategies, such as MPEAK (multi-peak), F0, the first formant, and the second formant are e tracted and used to modulate the electrical pulse's firing, errors are induced in formant e tractions, especiall in the situations where the speech signals are embedded in noise [1]. According to the CIS strateg , the envelope information of band-pass filtered speech sounds are e tracted and used to modulate the amplitude of electrical stimulation pulses of implanted electrodes without preserving the phase information in speech sounds. Since the phase information is potentiall useful for improving CI listeners' speech perception [12], the present stud proposes a new CI speech-processing strateg , the simulated phase-locking stimulation (SPLS) strateg , which preserves part of phase information in original speech and would be useful for upgrading the function of a CI device b introducing phase-related modulation of stimulation-pulse intervals. To e perimentall evaluate the efficac of the SPLS strateg in processing Mandarin Chinese speech, we presented the acoustic stimulation of the SPLS strateg to normal-hearing Chinese listeners under either noise-masking or competing-speech-masking conditions.

Methods

Simulated Phase-Locked Stimulation Strategy

Figure 1 illustrates how the SPLS strateg e tracts envelopes of band-pass filtered signals and uses phase information to modulate pulse rates [1, 6]. A signal is pre-emphasi ed first and then decomposed into multiple frequenc bands b a bank of band-pass filters. Because in the present stud the filter-bank should not distort phases of input signal components, the ero-phase transfer function is used in the stage of band-pass filtering [13]. After that, the signal in each band goes through 2 signal pathwa s: envelope e traction and phase e traction. To e tract envelope information, the filtered signal is processed b the Hilbert transform and the e tracted envelope is then logarithmicall compressed to an acceptable d namic range for CI. The compressed envelope will be used to modulate the amplitude of pulse trains that are interleaved among electrodes. To e tract phase information, the ' ero-crossing detection' process was used to record ever ero-crossing time of the narrow-band signal in each band. The phase information will be used to decide the firing time of pulse trains.

The pulse-firing strateg of SPLS simulates the neural mechanism of human hearing. In the human auditor s stem, the nerve firings occur at roughl the same phase of the waveform each time. However, there is also a difference between low and high frequencies. In detail, a single auditor nerve fiber fires on ever c cle of tone stimulus in the low-frequenc range and does not necessaril fire on ever c cle of tone stimulus in the high-frequenc range. In SPLS, the electrical stimulation pulses of each channel occur at the ero-phase of the signal in the corresponding channel. For a given channel whose center frequenc is below 1,200 H , pulses fire at ever ero-crossing time detected from the band-pass filtering signal. Otherwise, pulses fire once ever $\lceil f/1{,}200 \rceil$ ero-crossing times, where *f* is the center frequenc , and $\lceil . \rceil$ means the smallest integer bigger than f/1,200. The amplitude of the pulse is modulated b the e tracted envelope.

For the CIS strateg , the periods between pulses in each channel are fi ed and simultaneous firing across channels can be avoided. However, for the SPLS strateg , the pulse rate in each channel is changed according to phase information, and simultaneous firing between 2 adjacent channels will happen. So, we measured the possibilit of simultaneous firing between 2 adjacent channels on a 49-second piece of sound (including male or female English speech, Chinese speech, and a piece of music), which was processed b the SPLS strateg with 8 channels. When 2 pulses of 2 adjacent channels, respectivel , fired at the same time, this firing was counted as a simultaneous firing. The final percent of simultaneous firing was 1.9%, which was too small to use additional inhibitor procedures.

Acoustic Simulation

Previous studies have confirmed that e amination of normal-hearing listeners' responses to acoustic simulation of a CI processing strateg is useful for evaluating these strategies [14]. Thus, the effectiveness of the SPLS strateg was inn(t)-8 tev(i)-2lgstesin thesr a

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ant is quarrelling with a bag', whose direct Chinese translation sounds like: 'Yi1 hi1 ma3 i3 heng4 ai4 uan1 nao4 i1 ge1 shu1 bao1', all the 3 underlined words are the ke words [18]. Target speech stimuli were spoken b a oung female speaker, and tested in a quiet environment or 1 of the 2 masking conditions,

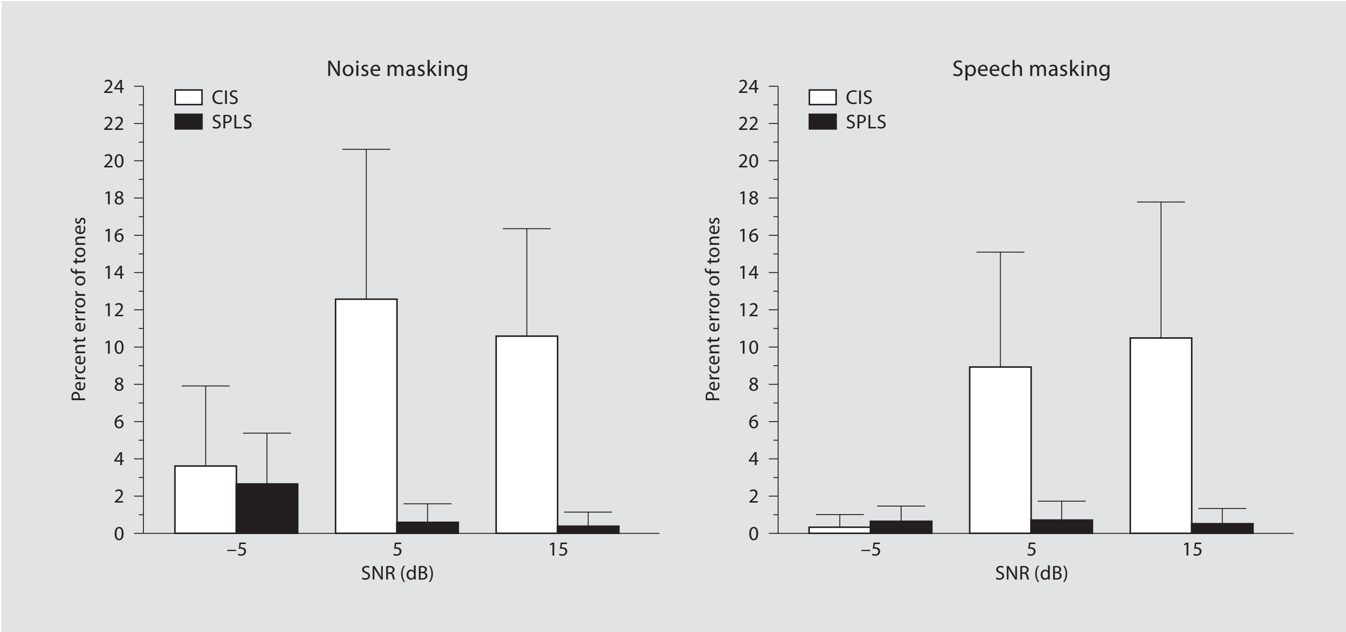

Fig. 3. Mean percent-error in recognition of tones across 12 subjects as a function of SNR for each of the 2 processing strategies under 2 masking conditions: stead -spectrum-noise masking and speech masking. The error bars indicate the SD of the mean.

ANOVA anal sis shows that the difference is significant, F(1, 11) = 55.288, MSE = 372.09, p = 0.000.

As shown in figure 2, under masking conditions speech recognition increased with the increase of the SNR in all conditions, and the recognition of the target speech processed b SPLS was much larger than that processed b CIS in both noise and speech-masking conditions. The main effect of SNR was significant, F(1, 11) = 448.33, MSE = 4.642, p = 0.000, the main effect of processing strateg was significant, F(1, 11) = 656.473, MSE = 4.821, p = 0.000, and the main effect of masking t pe was significant, F(1, 11) = 102.406, MSE = 0.471, p = 0.000.

To e amine whether the SPLS strateg was also beneficial to recognition of tones, we anal ed the 'tone error' in sentence repeating across 12 subjects. The percent error in recogni ing tones was defined as the percentage of the number of Chinese characters whose s llable was correctl recogni ed but whose tone was not correctl pronounced out of the number of 108, which was the total number of ke word characters in each list. Under the quiet condition, the mean percent-error in recognition of tones was 0.29% for the SPLS strateg and 8.17% for the CIS strateg . Under masking conditions, the percent error in recognition of tones was much less for the SPLS strateg than for the CIS strateg . Under the low SNR condition (SNR = 5 dB), the difference between the SPLS strateg and the CIS strateg was not significant. However, when the SNR was increased to 5 or 15 dB, the percent error in recognition of tones was decreased more for the SPLS strateg than for the CIS strateg (fig. 3).

Discussion

As pointed out b Fu et al. [19], there are additional needs for developing speech-processing strategies to specificall improve functions of cochlear implant devices for recogni ing tonal languages, such as Chinese. Phase information is presented in speech for normal listeners, and is important not onl for sound locali ation, but also for signal recognition in noise [12]. In the present stud , adding phase information with the SPLS method into target speech remarkabl improved listeners' recognition performance in quiet. More importantl , additional phase information presented in target speech released the speech from noise and speech maskers.

It is well known that firings of the auditor nerve to pure tones are phase locked in the low-frequenc range. CI devices create auditor sensation of sounds b direct- l stimulating the auditor nerve. If the interval of stimulation pulses at a stimulated site is modulated b phase information provided b the SPLS strateg developed in this stud , the function of CI devices for processing tonal speech and even music would be improved. In addition, it would be interesting to stud whether the SPLS is also beneficial for processing western languages, such as Eng-

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