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Electrophysiological Correlates of Spectral Discrimination for Cochlear Implant Users

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***Abstract*—A cochlear implant (CI) can partially restore hearing in patients with severe to profound sensorineural hearing loss. Proper programming and evaluation of the CIs are key aspects determining success in the restoration of hearing for patients. Recent evidence suggests that cortical auditory evoked potentials, elicited via an unattended oddball paradigm, can provide objective information on CI spectral discrimination abilities, which in turn may be useful for assessing speech perception performance. This study investigates the applicability of an acoustic change paradigm for objective evaluation of CI users' ability to resolve spectral content via single channel electroencephalography. Acoustic change complex (ACC) responses were obtained from 13 CI users and correlated with psychoacoustic spectral discrimination abilities. The applicability of the acoustic change paradigm was compared to that of the unattended oddball paradigm. The neural spectral discrimination threshold, estimated via the ACC responses, showed a non-significant correlation with the behavioral spectral discrimination threshold. In contrast, the neural spectral threshold estimated via an unattended oddball paradigm showed a significant correlation with the behavioral threshold. Results suggest that the unattended oddball paradigm is a more robust paradigm than the ACC to objectively evaluate CI users' ability to resolve spectral ripples. Nonetheless, the ACC can be used in some CI users and may be considered as an additional tool for objective evaluation of CI performance.**

I. Introduction

Hearing impairment is one of the most frequent sensory deficits in the human population [1], and cochlear implants (CI) have successfully restored partial hearing to over 300,000 people worldwide [2]. There is a critical need to provide clinicians and audiologists with the appropriate tools to ensure optimal rehabilitation for this rapidly growing population, particularly for pediatric CI users. Objective measures of CI performance have shown a promising future for the evaluation of hearing rehabilitation in adult and infant CI user populations.

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It has been suggested that cortical auditory evoked potentials (CAEP) can be used to evaluate speech perception performance in CI populations [3]. There are a number of electroencephalography (EEG) paradigms that can be used to elicit CAEPs. The unattended oddball paradigm (i.e. mismatch negativity) allows the exploration of higher order auditory processing in subjects with different clinical conditions and minimal effort of engaged attention [4]. In a previous study by our group, we developed an objective metric of CI spectral discrimination with an unattended oddball paradigm via single channel EEG [5]. Nonetheless, other CAEPs such as the acoustic change complex (ACC) have also been proposed to probe cortical discrimination abilities in normal hearing and CI populations [6-10]. Previous research suggests that it may be possible to measure behavioral and physiological spectral discrimination in CI users by means of acoustic change complex (ACC) paradigms [9, 10].

The study presented in [10] showed a correlation between electrophysiological and behavioral spectral ripple discrimination via single-interval change presentation (i.e. ACC for electrophysiological discrimination and yes/no for behavioral discrimination). Furthermore, it validated the relationship suggested in [11] between spectral ripple discrimination and speech perception performance in noise. The present study explored the possibility to employ an ACC paradigm, in combination with the CI artefact attenuation methodology described in [12], for evaluation of spectral ripple discrimination in CI users as an alternative method to the metric previously proposed in [5].

The possibility to employ different methods for evaluating spectral discrimination in CI users, without the need to modify a clinic-friendly set-up, may be an attractive option for clinicians and audiologists when assessing CI rehabilitation and performance.

II. Methods

A. *Participants*

13 CI participants volunteered for this study, 10 recruited from the National Cochlear Implant Programme at Beaumont Hospital in Dublin, Ireland and 3 recruited from the Hearing and Speech Lab at the University of California in Irvine, USA. Inclusion criteria were: postlingually implanted participants, age restricted from 18-75 years, absence of any additional linguistic or developmental problems and implant switch-on date no shorter than 6 months prior to the study. All participants provided informed consent and the procedures

were approved by the corresponding ethical authorities at each location.

B. *Electrophysiological and Behavioral Paradigms*

1) Acoustic Change Paradigm

Electrophysiological ACC was elicited to a successive presentation of 120 acoustic change stimuli. The stimulus presentation rate was 0.33 Hz with an inter-stimulus interval of one second. At least four 6-minute recordings were acquired from each participant with different stimuli. Recording took place inside an electrically isolated room and participants were instructed to ignore the stimulus presentation and direct their attention to a silent, captioned film.

Behavioral acoustic change discrimination was measured via a single-interval psychoacoustic test. Acoustic change stimuli and non-change stimuli were presented randomly with a total of 120 presentations each. Upon stimulus presentation, the participant was asked to press a button, on a graphical interface, indicating 1 if there was no change in the stimulus or 2 if an acoustic change was present. At least four psychoacoustic tests were performed with the same stimuli as in the ACC paradigm. A psychometric curve was fitted to the behavioral results to determine psychoacoustic discrimination thresholds as the point where correct identification of acoustic change dropped below 50%.

2) Unattended Oddball Paradigm

A mismatch waveform (MMW) was elicited by presenting a set of standard and deviant auditory stimuli in an unattended oddball paradigm. The stimulus repetition rate was 1Hz and the occurrence of a deviant presentation was random with a probability of 10%. At least four 15-minute recordings were acquired from each participant with different stimuli. These recordings also took place inside an electrically isolated room, with the participant sitting comfortably while attending to a silent, captioned film.

Due to the difference in the nature of the ACC and unattended oddball paradigms, an additional behavioral discrimination test was conducted. A psychoacoustic two-up, one-down, adaptive three-alternative forced-choice test was repeated five times by each participant to determine their mean behavioral spectral discrimination threshold. A sequence of three stimuli was presented in one run, two of which were standard and one of which was the deviant. The participant had to identify the deviant stimulus by pressing on a graphical interface. The test ran until 13 reversals occurred and the discrimination threshold was calculated as the mean of the last eight reversal values.

C. *Stimuli*

Spectrally rippled broadband noise stimuli were generated for both paradigms. The broadband noise was created via summation of 4000 pure tones with frequencies from 100 Hz to 8,000 kHz. The spectral ripple was created with a full wave rectified sinusoidal envelope on a logarithmic amplitude scale and with maximum amplitude of 30 dB peak-to-valley as described in [11]. Spectral peaks were equally distributed on a logarithmic frequency scale, and the number of spectral peaks per frequency octave defines the ripple density of the stimulus (RPO).

Acoustic change stimuli were 2000 ms in duration with a spectral inversion at the mid-point. Spectral inversion was a phase shift of the sinusoidal ripple envelope of $\pi/2$ with respect to the first 1000 ms of the stimulus. Standard and deviant stimuli generated for the unattended oddball paradigm were 500 ms in duration and the deviant stimulus was spectrally inverted with respect to the standard stimulus. Both stimuli had equal RPO density. Fig. 1 illustrates the spectrogram for standard (A, left), deviant (A, right) and acoustic change stimuli (B) generated at one RPO.

Stimuli were delivered electrically, through the auxiliary input of the CI's speech processor at a comfortable loudness level.

D. *Data Recording*

Single channel EEG recordings were acquired using a customized high sampling rate and high bandwidth system previously developed by the authors [5, 12]. Electrodes were placed at the vertex (Cz) and the mastoid, contralateral with respect to the tested ear. The system ground was located at the collar bone. The EEG signal was pre-amplified via a Stanford Research Systems biological pre-amplifier (filter settings: 0.03 Hz – 100 kHz) and then digitized into a PC via a National Instruments analog to digital converter (sampling rate: 125 kHz).

E. *Signal Processing*

1) Acoustic Change Paradigm

Raw EEG data were segmented into long epochs of 300 ms pre-stimulus to 2500 ms post-stimulus onset to avoid filter edge effects. The three stage CI artifact attenuation procedure developed in [12] was applied to the ACC responses. Baseline correction of 150 ms pre-stimulus was applied to the filtered epochs. Epochs were filtered with a pass-band (2-20 Hz) 2nd order Butterworth filter.

The ACC amplitudes were measured as a ratio of the change response amplitude, generated after the spectral inversion, over the amplitude of the stimulus onset response. The stimulus onset response is equivalent to the N1-P2 complex, characteristic of CAEPs. The change response is

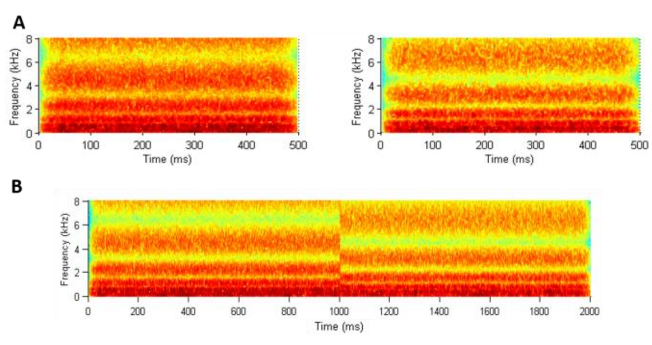

Figure 1: Description of a one RPO stimuli **A:** Stimuli spectrogram as separate standard (left) and deviant (right) presntation as employed in the unattended oddball paradigm. Standard and deviant presentations had equal number of RPOs but inverted spectral content. **B:** Stimulus spegtrogram of a fused spectral change presentation as employed in the acoustic change paradigm. Spectral inversion occurred at the midpoint of the simulus duration.

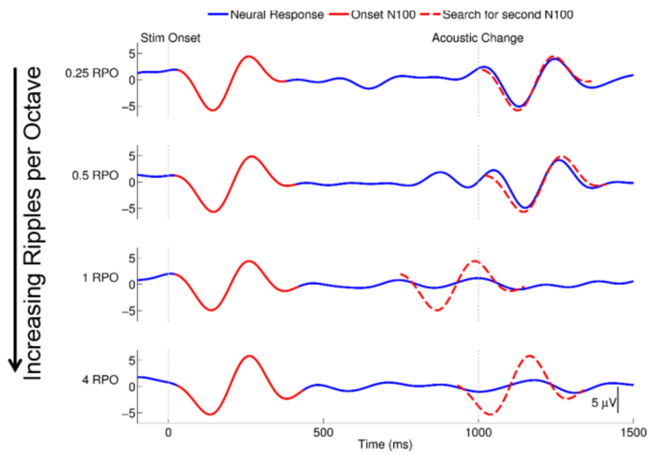

Figure 2: Template search of acoustic change responses based on the stimulus onset response. Identifiable ACC responses can be observed at 0.25 and 0.5 RPO densities while no ACC responses are evident at 1 and 4 RPO densities.

generated approximately 100 ms after the spectral inversion and it is similar in morphology to the N1-P2 response but smaller in amplitude. For each RPO density, the N1-P2 response was manually selected from a region of interest of 90 to 250 ms after stimulus onset. In order to identify the change response, a normalized version of the selected N1-P2 response was cross-correlated with the normalized region of interest of 1090 to 1250 ms after stimulus onset. The time stamp of maximum correlation was defined as the change response. Fig. 2 illustrates this template search mechanism. N1-P2 responses were manually selected at each RPO density and the corresponding template was located after the acoustic change (i.e. 1000 ms after stimulus onset). At RPO densities of 0.25 and 0.5 the change response was located using a template search based on the onset response whereas at RPO densities of 1 and 4 no change response was identified.

The neural spectral ripple discrimination threshold was defined as the RPO density where the ACC amplitude dropped below 11%. This value was selected based on the average noise floor of each participant's recording.

2) Unattended Oddball Paradigm

MMW were calculated with the methodology proposed in [5] and it will only be briefly described here. Raw EEG data were segmented into long epochs of 300 ms pre-stimulus to 800 ms post-stimulus onset. Epochs were separated into standard and deviant and averaged across each type. Averaged epochs were filtered with a pass-band (2-20 Hz) 2nd order Butterworth filter. Baseline correction of 150 ms pre-stimulus was applied to the filtered epochs. MMW were calculated as the difference waveform resulting from subtracting the standard response from the deviant response. The noise floor of the signal was calculated via a bootstrap difference waveform calculated from the standard epochs. The area under the curve of the MMW above and below (+/-) the noise floor was deemed as a significant response.

Fig. 3 illustrates how a clear MMW response to a spectral density of 0.25 RPO decreases as the spectral density increases to 0.5 RPO, 1 RPO and 2 RPO.

The neural spectral discrimination threshold was defined as the point when the MMW area under the curve dropped below a significant level which was statistically derived from the data.

III. Results

1) Behavioral Results

Psychoacoustic spectral ripple discrimination thresholds via the single interval forced choice task were in the range of 0.35 to 5.22 (mean= 1.74, standard deviation= 1.33) RPO. In two participants, the fitting of the psychometric function was not possible due to ceiling effects. Spectral discrimination thresholds for the same participants via the three-alternative forced-choice paradigm were in the range of 0.24 to 2.60 (mean= 1.05, standard deviation= 0.73).

2) Electrophysiological Results

Neural estimates of spectral discrimination via the ACC paradigm could only be derived in seven participants with a mean threshold of 1.01 (standard deviation= 0.72) RPO. Neural thresholds via the unattended oddball paradigm were successfully derived in 11 participants with a mean threshold of 1.21 (standard deviation= 0.89) RPO.

Fig. 4 shows the linear regression of the behavioral thresholds with the neural thresholds for both methods, ACC on the left and unattended oddball on the right. The ACC correlation of the seven neural thresholds with the single interval psychoacoustic thresholds was non-significant (r^2=0.55, p-value>0.05). The unattended oddball correlation of the 11 neural thresholds with the three-alternative forced-choice psychoacoustic threshold was significant (r^2= 0.37, p-value<0.05). Individual metric performance can be seen in Fig. 5.

IV. Discussion

The present study compared two different methods to objectively estimate spectral ripple discrimination in a population of CI patients. The ACC was evaluated as a

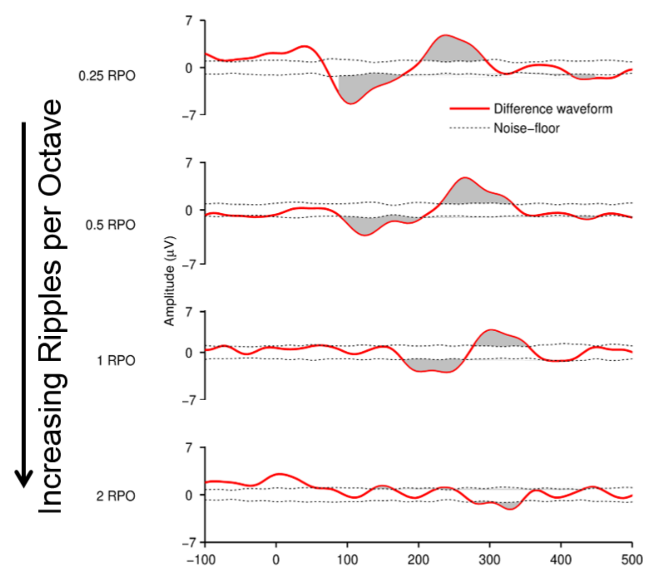

Figure 3: Exemplary data for one participant showing sequential fading of the MMW response as the spectral ripple density increases from 0.25 RPO to 2 RPO.

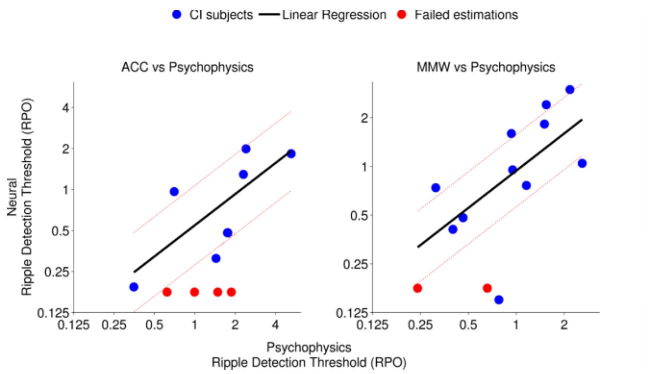

Figure 4: Correlation between the behavioral and neural spectral ripple discrimination. Red lines inidcate 95% confidence intervals. ACC paradigm on the left (correlation coefficient= 0.76, r^2=0.55, p>0.05), MMW on the right (correlation coefficient= 0.76 ,r^2=0.37, p<0.05).

potential CAEP for assessing spectral ripple discrimination and was compared to the unattended oddball method developed in [5]. This study confirms the robustness of the unattended oddball paradigm as an objective metric and presents the ACC as an additional objective metric.

A desirable advantage of the ACC paradigm over the unattended oddball paradigm is the shorter acquisition time, six minutes for the ACC vs 15 minutes for the unattended oddball paradigm. However, the representation of the spectral inversion in the ACC stimuli may generate additional temporal cues such as the switching on and off of stimulation electrodes allowing the CI patients to distinguish a change. An evidence of this effect may be the ceiling effect in two participants where they were able to discriminate changes in the sound at all RPO densities whereas their three-interval forced-choice tests indicated lower discrimination abilities.

It is conceivable that the lack of an ACC response, in some participants, is due to the high noise floor in the recording session rather than from the paradigm. Nonetheless, the unattended oddball paradigm, recorded during the same session yielded better results. The effect of stimulus delivery must be further investigated. It is possible that spectral ripple inversion may be clipped due to the 'fast attack' of the automatic gain control in the speech processors, preventing an ACC response. Electrodograms of the change stimuli could clarify this theory. This effect, in addition to a different signal processing approach, may explain why ACC were always present in [10], where the stimuli were delivered in free field, as opposed to this study.

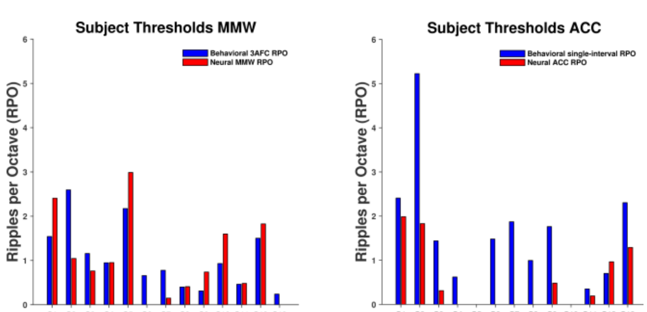

Figure 5: Individual subject perfomance shown in contrast with the corresponding behavioral trheshold. MMW estimantes compared to the three-alternative forced-choice (3AFC) psychoacoustic on the left. ACC estimates compared to the single-interval psychoacoustic on the right.

V. Conclusions

The present results suggest that it is possible to use the ACC in a single channel EEG acquisition system as an alternative to estimate spectral ripple discrimination in some CI patients. Despite its longer acquisition time, the unattended oddball paradigm is more robust than the ACC measure in estimating the behavioral spectral resolution for the described stimulation protocol.

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