35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Auditory Mismatch Negativity in Cochlear Implant Users: A Window to Spectral Discrimination

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***Abstract*—A cochlear implant (CI) can partially restore hearing in patients with severe to profound sensorineural hearing loss. However, the large outcome variability in CI users prompts the need for more objective measures of speech perception performance. Electrophysiological metrics of CI performance may be an important tool for audiologists in the assessment of hearing rehabilitation. Utilizing electroencephalography (EEG), it may be possible to evaluate speech perception correlates such as spectral discrimination. The mismatch negativity (MMN) of 10 CI subjects was recorded for stimuli containing different spectral densities. The neural spectral discrimination threshold, estimated by the MMN responses, showed a significant correlation with the behavioral spectral discrimination threshold measured in each subject. Results suggest that the MMN can be potentially used to obtain an objective estimate of spectral discrimination abilities in CI users.**

I. Introduction

Hearing impairment (HI) is the most frequent sensory deficit in human populations, being present in over 250 million people globally [1]. Patients suffering from HI are subject to social isolation due to their reduced capability to communicate and interact with their surroundings. A cochlear implant (CI) partially restores hearing in patients suffering from severe to profound sensorineural HI by electrically stimulating the auditory nerve. According to the Food and Drug Administration (FDA), as of December of 2010, over 219,000 people around the globe have received a CI [2].

The large outcome variability in CI users, such as the variable speech perception performance among users, prompts the need for more objective measures of CI speech perception performance [3]. Firszt et al. reported a correlation between CI users' speech perception abilities and mid-latency cortical auditory evoked potentials (CAEP) elicited by simple stimuli [4]. The use of complex stimulation, such as spectrally rippled noise instead of pure tone stimulation, may be better at characterizing a CI user's neural processing abilities as suggested by psychoacoustic studies [5]. 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 [6], [7].

The mismatch negativity (MMN) is a CAEP paradigm that allows the exploration of high order auditory processing in subjects with different clinical conditions and with minimal effort or engaged attention [8]. The present study explores the possibility to employ MMN, combined with complex stimuli, in a clinical set-up as an electrophysiological metric for spectral discrimination of CI users.

An electrophysiological metric of spectral discrimination may be a powerful tool for the audiologists when assessing speech rehabilitation progress in CI users. An objective metric may allow an improved evaluation of hard-to-test adult CI patients as well as enabling an objective examination of pediatric populations where behavioral testing is not possible.

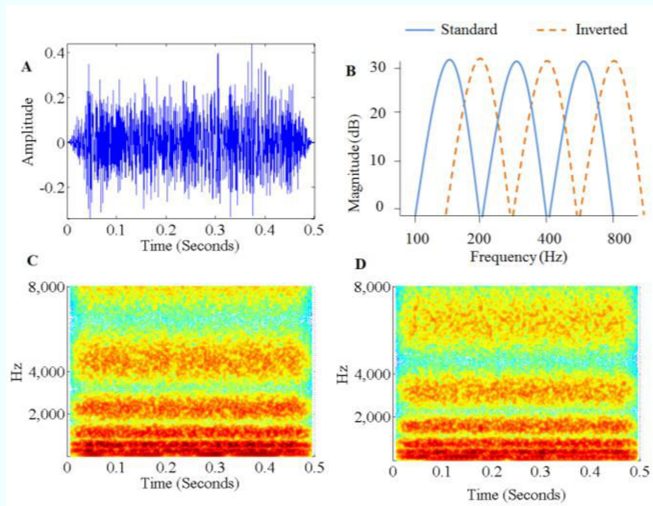

Figure 1: Description of one RPO stimuli A**:** Stimulus representation on the time domain. **B:** Sinusoidal spectral ripple envelope applied to create the standard and inverted stimuli with a ripple amplitude of 30dB peak to valley. **C:** Spectral content of the standard stimulus at one RPO. **D:** Spectral content of the inverted stimulus at one RPO.

This research was funded by a Common European Master's course in Biomedical Engineering (CEMACUBE) scholarship and the Graduate Research Education Programme in Engineering awarded by the Higher Education Authority to A. Lopez-Valdes and a Marie Curie Fellowship to M. McLaughlin.

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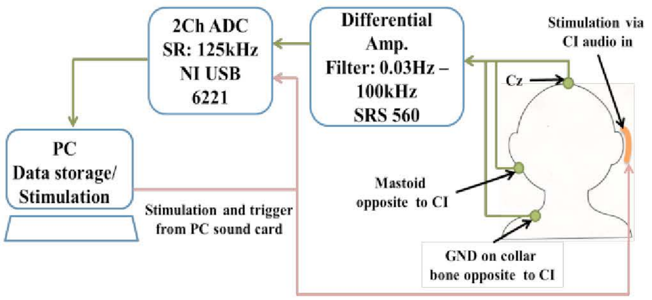

Figure 2: Schematic layout of the high sample rate and high bandwidth single channel EEG acquisition system.

II. Methods

A. Background

10 CI subjects were recruited from the National Cochlear Implant Programme at Beaumont Hospital in Dublin, Ireland. Inclusion criteria were: postlingually implanted subjects, age restricted from 18-75 years, absence of any additional linguistic or developmental problems and implant turn-on date no shorter than 6 months prior to the study.

The MMN was elicited by presenting a set of standard and deviant auditory stimuli, fed directly to the CI via the auxiliary input of the speech processor. The stimulus repetition rate was 1Hz and the occurrence of a deviant presentation was random with a probability of 10%. Five 10-minute MMN recordings were acquired from each subject. Recordings took place inside an electrically isolated room, with the subject sitting comfortably while viewing a silent film.

In addition to the electrophysiological measurement, spectral discrimination was assessed with psychoacoustic testing for each subject. A behavioral adaptive three-alternative forced-choice test was repeated five times by each subject to determine their mean behavioral spectral discrimination threshold.

B. Stimuli

The standard stimulus (90%) was spectrally rippled broadband noise; the deviant (10%) was the inverted version, having an equal number of ripples per octave (RPO). The broadband noise was created by a summation of 4000 pure tones with frequencies from 100Hz 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 by [5]. Fig. 1 illustrates the spacing of the spectral peaks, as well as the difference in frequency content of the standard and the deviant stimuli having both a spectral density of one RPO. Spectral peaks were equally distributed on a logarithmic frequency scale. The sinusoidal ripple envelope, for the inverted stimulus, had $\pi/2$ phase shift with respect of the one used for the standard stimulus. Stimuli were delivered electronically, through the auxiliary input of the CI's speech processor, as indicated in Fig. 2.

C. Electroencephalography (EEG) Recording System

Single channel EEG recordings were acquired using a customized high sampling rate and high bandwidth system.

Fig. 2 shows the layout of the above described system. Electrode positions 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: 0.03Hz – 100kHz) and then digitized into a PC via a National Instruments analog to digital converter (sampling rate: 125kHz).

Sampling rate and filter settings exceed those typically employed in conventional EEG acquisition systems. Sampling rate and filter setting were chosen to clearly acquire and resolve the CI related artifact, caused by the CI stimulation pulses as shown in Fig. 3.

D. Signal Processing

After inspection of the recordings, it was identified that the recorded signal was composed of three elements: 1) the neural response over time NR(t); 2) high frequency artifact over time HFA(t), generated by the CI electrical stimulation; and 3) DC artifact assumed to be related to the stimulation pulse amplitude (PA) over time DCA(PA,t). Hence:

$$SIG(t) = NR(t) + HFA(t) + DCA(PA, t) \quad (1)$$

The acquisition system allows for clear acquisition of large amplitude and high frequency CI related artifact. Fig. 3 shows the full effect, captured with the customized acquisition system, of the CI electrical stimulation. The large amplitude (> 1000 μV) and the high frequency (>1000 Hz) generated by the CI during the stimulus presentation, compromises the acquisition of a CAEP.

Artifact attenuation was performed as described by Mc Laughlin et al. [9] and its briefly described below. Fig. 4 is a graphical representation of the steps involved in the attenuation process.

The signal described in (1) was band-pass filtered, with a 2nd order Butterworth filter digitally implemented, with cut-off frequencies of 2Hz – 30Hz in order to reduce the high frequency artifact, yielding:

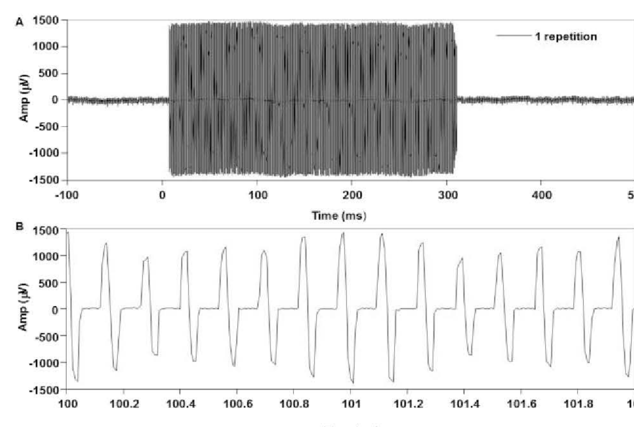

Figure 3: A) 600ms epoch of EEG recording of a CI subject during a 300ms stimulus presentation. B) 2ms zoom of the recorded EEG epoch showing the biphasic pulses of the CI stimulation.

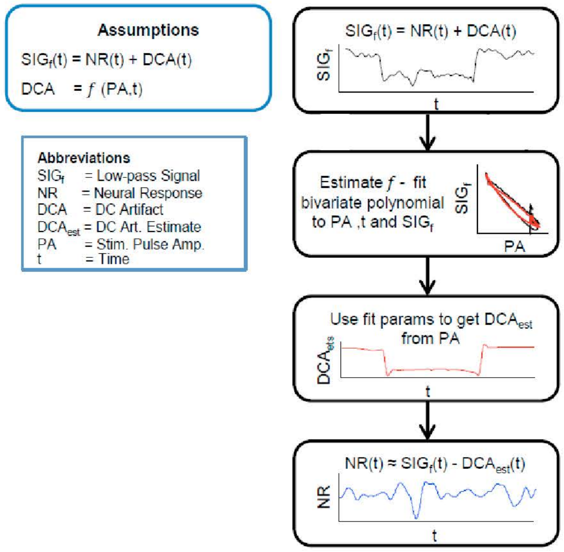

Figure 4: The desired neural response is recovered from the low-passed recorded signal by substracting a bivariate polynomial estimation of the DC artifact, assumed to be related to the stimulation pulse amplitude and time.

$$SIG_f(t) = NR(t) + DCA(PA,t) \quad (2)$$

Given our assumption that the DC artifact is a function of PA and time, an estimate of the DC artifact (DCAest(t)) was calculated with a bivariate polynomial fit of the stimulation pulse amplitudes as depicted in Fig. 4.

Neural responses were recovered by subtracting the DC artifact estimate from the filtered signal described in (2) in the form:

$$NR(t) \approx SIG_f(t) - DCA_{est}(t) \quad (3)$$

III. Results

The MMN was calculated by subtracting the neural response elicited by the standard stimulus from the neural response elicited by the deviant stimulus. To define a neural spectral discrimination threshold, the spectral density of the stimuli was increased (i.e. 0.25RPO, 0.5RPO, 2RPO) until the area under the curve between the MMN and the noise floor of the signal had dropped below a significance level. The noise floor of the signal was determined as +/- one standard deviation of the signal, using a boot-strap method to the standard responses.

Fig. 5 illustrates how a well-defined MMN response to a spectral density of 0.25 RPO (Fig. 5A) decreases as the spectral density increases to 0.5 RPO (Fig. 5B). The MMN response drops below the noise level as the spectral density increases to 2 RPO (Fig. 5C), thus losing the discrimination capability.

An adaptive three-alternative forced-choice test was performed to every subject to determine the behavioral spectral discrimination threshold for validation of the MMN metric.

A significant correlation (r^2=0.66, p=0.004175)) was found between the neural RPO detection threshold and the behavioral RPO detection threshold in CI subjects, as shown in Fig. 6.

IV. Discussion

The aim of this study was to investigate if an objective metric based on MMN estimates the spectral discrimination ability of CI users. Such a metric would have great potential as a tool for assessment of speech perception performance in CI users.

The results presented in this study indicated that the MMN can estimate the spectral processing abilities of CI users. Given the known correlation between speech perception and the behavioral spectral discrimination threshold [5], it is predicted that there is a correlation with neural spectral discrimination threshold and speech perception; however, this remains to be tested.

The findings show that the correlation between the MMN metric and the behavioral metric, in this study, is not one to one. This may be attributed to the difference on the cognitive load required between the three-alternative forced-choice test and the MMN paradigm. A matched, MMN-like task to determine the behavioral spectral discrimination thresholds may be used to explore this further.

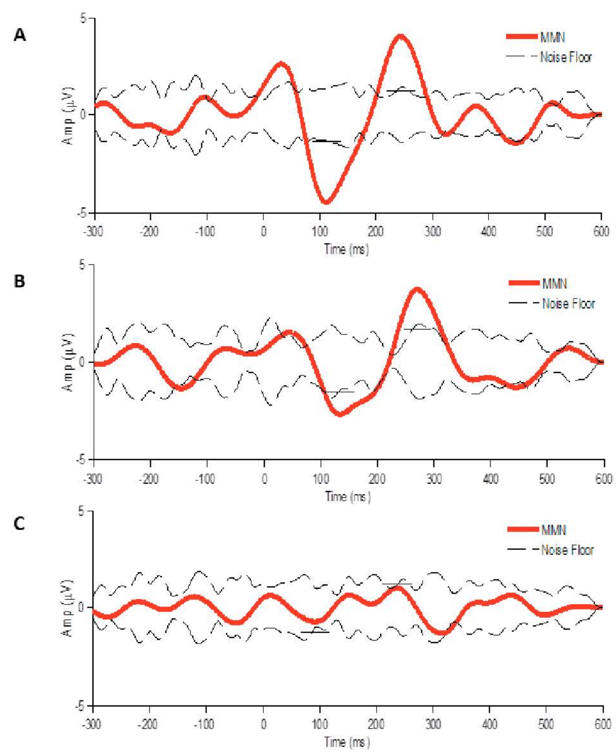

Figure 5: Sequencial fading of the MMN response as the simuli increases in spectral ripple density. **A:** MMN elicited to a stimuli containing 0.25 RPO. **B:** MMN elicited to a stimuli containing 0.5 RPO. **C:** MMN elicited to a stimuli containing 2 RPO.

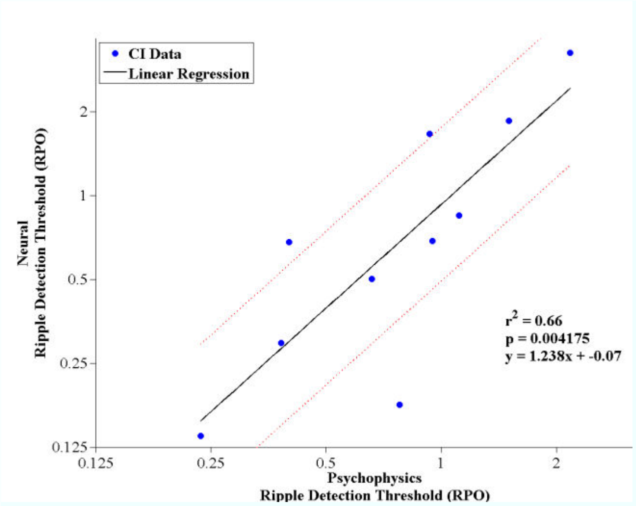

Figure 6: Correlation between the behavioral spectral ripple detection versus the neural spectral ripple detection of 10 CI subjects. (r^2=0.66, p=0.004175)

Previous studies have investigated the possibility of using EEG as an objective metric for spectral discrimination. Won et al. [6] developed a single interval ACC paradigm for estimation of behavioral and physiological spectral discrimination thresholds in CI users. Findings show that the cognitive load of the discrimination task is likely to influence the number of discriminable ripples per octave [6]. Stoody et al. [10] investigated the use of MMN for spectral modulation contrast detection in normal hearing subjects. Their findings show presence of the MMN at 10dB and 20dB of spectral modulation contrast; however, there was no indication of a threshold metric [10].

The neural spectral discrimination findings of this study are consistent with the behavioral spectral discrimination findings by Won et al. [5] with respect to CI users having lower spectral discrimination than normal hearing subjects.

This study aims to provide an objective metric to assess spectral discrimination of CI users during normal use of their device. For this reason, the inclusion of the signal conditioning stages by the speech processor may yield a better approach than bypassing the CI control and directly manipulating the stimulating electrodes as used by Won et al. [6] and Brown et al. [7].

V. Conclusions

This study developed an objective method to estimate the spectral discrimination abilities in CI users based on EEG recordings and a MMN paradigm.

MMN is a simple and straight-forward EEG paradigm that can be performed in a clinical environment. Using a single channel EEG recording system reduces the acquisition time for the clinician and represents a more comfortable scenario for the patient to be tested.

The literature suggests that with the use of other EEG paradigms such as the ACC may also be possible to estimate the spectral discrimination threshold in CI users [6], [7]. Nonetheless a comparison between the effectiveness of MMN and ACC as an estimate of spectral discrimination is yet to be performed.

Research towards a clinical objective metric for evaluation of CI performance may provide the audiologist with additional tools for an optimal tailoring of individual rehabilitation processes. This in turn will maximize the outcome of the CI and contribute to reduce the large outcome variability currently observed among the CI user community.

Acknowledgment

The authors would like to thank the Higher Education Authority (HEA), in Ireland, and the European Commission's Marie Curie Fellowship for supporting this research.

References

[1] World Health Organization (WHO), "Deafness and Hearing Impairment," *Journal*, [online], pp. 5, (Date 2012), Available http://www.who.int/mediacentre/factsheets/fs300/en/index.html.

[2] National Institute of Deafness and other Communication Disorders (NIDCD), "Cochlear Implants," [online], (Date 2011), Available http://www.nidcd.nih.gov/health/hearing/pages/coch.aspx/.

[3] F.G. Zeng, "Trends in cochlear implants," *Trends in amplification*, vol. 8, (no. 1), pp. 1-34, 2004.

[4] J.B. Firszt, R.D. Chambers, Kraus, and R.M. Reeder, "Neurophysiology of cochlear implant users I: effects of stimulus current level and electrode site on the electrical ABR, MLR, and N1-P2 response," *Ear and Hearing*, vol. 23, (no. 6), pp. 502-15, Dec 2002.

[5] J.H. Won, W.R. Drennan, and J.T. Rubinstein, "Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users," *JARO Journal of the Association for Research in Otolaryngology*, vol. 8, (no. 3), pp. 384-92, Sep 2007.

[6] J.H. Won, C.G. Clinard, S. Kwon, V.K. Dasika, K. Nie, W.R. Drennan, K.L. Tremblay, and J.T. Rubinstein, "Relationship Between Behavioral and Physiological Spectral-Ripple Discrimination," *JARO-Journal of the Association for Research in Otolaryngology*, vol. 12, (no. 3), pp. 375-393, 2011.

[7] C.J. Brown, C. Etler, S. He, S. O'Brien, S. Erenberg, J.R. Kim, A.N. Dhuldhoya, and P.J. Abbas, "The electrically evoked auditory change complex: preliminary results from nucleus cochlear implant users," *Ear and Hearing*, vol. 29, (no. 5), pp. 704-17, Oct 2008.

[8] R. Naatanen, T. Kujala, C. Escera, T. Baldeweg, K. Kreegipuu, S. Carlson, and C. Ponton, "The mismatch negativity (MMN)--a unique window to disturbed central auditory processing in ageing and different clinical conditions," *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology*, vol. 123, (no. 3), pp. 424-58, Mar 2012.

[9] M. McLaughlin, A. Lopez Valdes, R.B. Reilly, and Z. Fang-Gang, "Cochlear Implant Artifact Attenuation in Late Auditory Evoked Potentials: A Single Channel Approach," *Hearing research*, In Review.

[10] T.M. Stoody, A.A. Saoji, and S.R. Atcherson, "Auditory Mismatch Negativity: Detecting Spectral Contrasts in a Modulated Noise1," *Perceptual and Motor Skills*, vol. 113, (no. 1), pp. 268-276, 2011.