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The potential of objective T-level determination in CI recipients using envelope following responses

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I: Introduction

Automatic and **objective Cochlear-Implant (CI) fitting** can be a solution to a number of challenges, associated with the fine-tuning of the stimulation settings of a CI. Problems such as requiring subjective feedback, time constraints and varying clinical expertise could be solved with an objectively performed fitting routine.

Electrically evoked auditory steady-state responses (EASSRs) are phase-locked responses to continuous amplitude-modulated electrical pulse trains. They can serve as objective measure to determine CI stimulation thresholds [1] and are also correlated with the modulation encoding ability of CI users and are therefore a potential **neural correlate of speech understanding performance**. Consequently, they are an interesting objective measure for the fitting.

A major challenge when recording EASSRs are the **electrical stimulation artifacts** of the implant, which contaminate the EEG recording. These artifacts are highly correlated with the EASSR and overlap the response in time as well as in the frequency domain. They are difficult to distinguish from the real response and may lead to a false-positive response detection in the absence of an EASSR.

The recently introduced EASSR detection and stimulation artifact removal method based on **system identification (SI)** [2] has shown promising results in detecting EASSRs in EEG recordings at different stimulation levels [3]. Interestingly, the same method can also be applied to EEG recordings following more complex stimuli than those from EASSRs. Using **envelope following responses** (EFR) [4] allows response latency determination within one EEG recording, which removes the chance of false-positive response detection without requiring several EASSR EEG recordings per stimulation condition. Furthermore, the stimuli are closer to actual speech stimuli with time variations in the envelope of the signal, making them ecologically more relevant for CI performance.

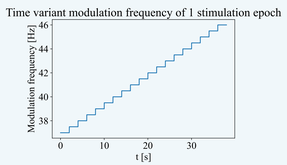
The goal of this work is to present **preliminary results** of an **objective T-level detection** procedure using the **envelope following response** following a **sweep stimulus**.

II: Stimulus definition

- Amplitude modulation with **increasing modulation frequency** f_m over epoch duration
- Discrete **frequency steps** of $0.5Hz$ (Δf)
- 2s per frequency step (T_{seg})
- Equal instantaneous phase between subsequent frequency steps

Time variant modulation frequency

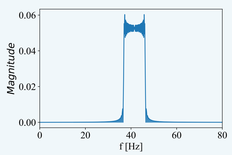
$$f_0 = 37Hz$$
$$f_{end} = 46Hz$$
$$f_m[k] = f_0 + \lfloor \frac{kT_s}{T_{seg}} \rfloor \cdot \Delta f$$



Discrete modulation frequency sweep $f_m(t)$

Time variant modulation of EFR stimulus

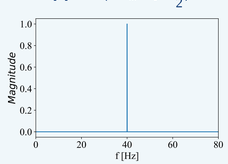
$$m[k] = \sin(2\pi f_m[k] k T_s + \frac{\pi}{2})$$



Magnitude spectrum of EFR modulation (with f_m sweep) shows frequency content over range of chosen frequencies (f_0 to f_{end}). This provides more input-output information within one recording and benefits the system identification.

Constant modulation of EASSR stimulus

$$m[k] = \sin(2\pi f_m k T_s + \frac{\pi}{2})$$



Magnitude spectrum of EASSR modulation shows frequency content only at one frequency (e.g. at $40Hz$).

III: Stimulation and measurement setup

Stimulation

- Amplitude-modulated pulse train
  - Symmetric biphasic, cathodic-first pulses
  - Phase width of clinical map, IPG $8\mu s$
  - **900pps**
  - Active electrode ICE15 in **Monopolar mode**
  - 7 stimulation levels within dynamic range of CI user and 1 sub-threshold stimulation
  - Fixed modulation depth of 50CL
  - Sweep of modulation frequencies as illustrated

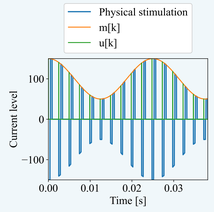


Illustration of physical EFR stimulation, modulation model $m[k]$ and input model $u[k]$ of artifact model.

Recording

- 8-channel Biosemi ActiveTwo Hyper-Rate EEG
- 5min recording per stimulation level
- Sample rate: 262.144kHz

Participant information

- 1 adult CI-user
- Cochlear Ltd. device

IV: Model definition and parameter estimation

Recording model

- Joint model of
  - Envelope model
  - Artifact model

$$\hat{\mathbf{z}} = \underbrace{\begin{bmatrix}\mathbf{M} & \mathbf{U}\end{bmatrix}}_{\mathbf{H}} \cdot \underbrace{\begin{bmatrix}\mathbf{b_{resp}} \\ \mathbf{b_{arti}}\end{bmatrix}}_{\mathbf{x}} + \mathbf{v}$$

Envelope model

- Response follows modulation $m[k]$ of stimulation
- $\mathbf{M}$ = lagged time series of modulation $m[k]$
- $\mathbf{b_{resp}}$ = impulse response of response FIR
- $\mathbf{v}$ = noise

$$\mathbf{r} = \mathbf{M} \cdot \mathbf{b_{resp}} + \mathbf{v}$$

Artifact model

- Pulsatile artifact with modulation $m[k]$
- $\mathbf{U}$ = lagged time series of modulated pulse train model $u[k]$
- $\mathbf{b_{arti}}$ = impulse response of artifact FIR
- $\mathbf{v}$ = noise

$$\mathbf{a} = \mathbf{U} \cdot \mathbf{b_{arti}} + \mathbf{v}$$

Joint parameter estimation with Tikhonov regularization

$$\hat{\mathbf{x}} = \begin{bmatrix}\hat{\mathbf{b}}_{\mathbf{resp}} \\ \hat{\mathbf{b}}_{\mathbf{arti}}\end{bmatrix} = (\mathbf{H}^\top\mathbf{H} + \alpha\mathbf{\Gamma}^\top\mathbf{\Gamma})^{-1}\mathbf{H}^\top\mathbf{z}$$

- "Banded regression"
- Beneficial for models with multicollinearity

Response FIR evaluated at modulation frequencies

$$FIR1(z = e^{j2\pi f_m}) = \begin{bmatrix}1 & e^{-jq2\pi f_m} & e^{-j2q2\pi f_m} & \dots & e^{-jMq2\pi f_m}\end{bmatrix} \cdot \mathbf{b_{resp}}$$

Response amplitude

$$A(f_m) = |FIR1(z = e^{j2\pi f_m})|$$

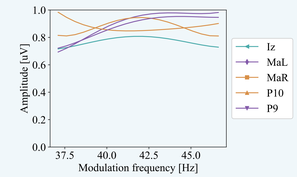
Response phase

$$\theta(f_m) = \angle FIR1(z = e^{j2\pi f_m})$$

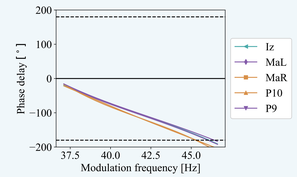
- Further details in [2],[3] (Follow Qr-code)

V: Preliminary results

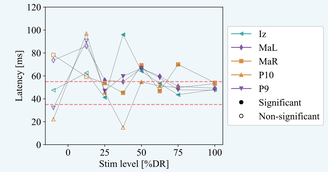
EFR amplitude and phase response of EEG recording at highest stimulation level (100%DR). Ipsilateral ■ contralateral ■ and central ■ EEG recording channels.



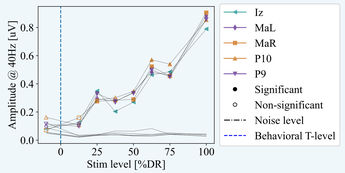
Amplitude response at 100%DR



Phase response at 100%DR



Determined response latency (from phase response) of EFR for all EEG recording channels over all stimulation levels. Expected latency range of response is indicated with red dashed lines.



Determined EFR amplitude growth function (response amplitude at $f_m(t) = 40Hz$ for all stimulation levels). Behavioral T-level indicated with blue dashed line.

Significant responses (statistically different from background noise) are indicated with filled plot points.

VI: Discussion and conclusion

- **Latency in expected range of 35-55ms** indicates good artifact removal and EFR presence [5]
- Non-significant response indicates good artifact removal and EFR absence

- ▶ Successful identification and separation of stimulation artifact and EFR in EEG recording
- ▶ Successful amplitude growth function recording with EFRs
- ▶ Possible objective T-level detection using EFRs
- ▶ Prevention of false-positive response interpretation using response latency from one EEG recording

VII: Acknowledgements and references

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