



Objective Measures of Loudness in Cochlear-Implant Hearing

Charlotte Garcia¹, Dorothee Arzounian^{1,2}, François Guérit¹ & Robert P. Carlyon¹

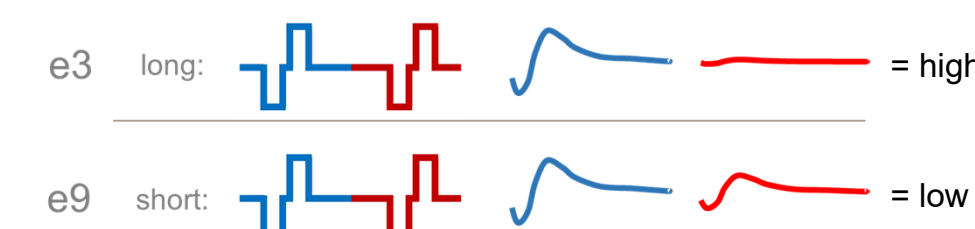
¹MRC Cognition & Brain Sciences Unit, University of Cambridge, Cambridge, United Kingdom | ²Institut Pasteur, INSERM, Paris, France

Introduction

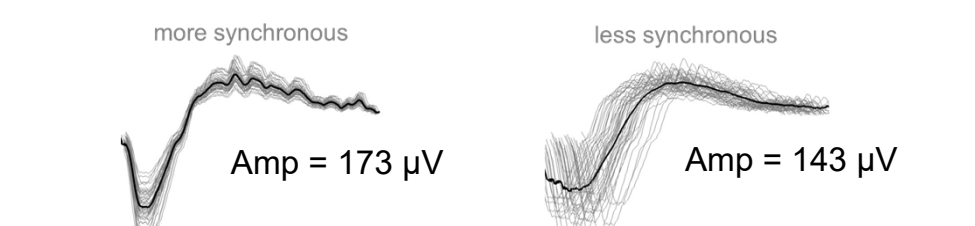
Electrically-Evoked Compound Action Potentials (ECAPs) capture the synchronous response of the auditory nerve (AN) to electrical stimulation. They are sometimes used to fit cochlear-implant (CI) programming levels. However, evidence that they correlate with behavioural measures of loudness is mixed, and largely based on comparisons *between* listeners. Furthermore, measurements from the Panoramic ECAP Method (Garcia et al 2021; 2024) show that ECAP amplitude can differ markedly between electrodes, within the same ear, despite being presented at similar (most-comfortable) loudness (MCL) and presentation rate.

Experiment 1 explored two peripheral factors that might affect ECAPs but not loudness and hence explain the discrepancy:

(1) Variation in (Absolute) Refractory Periods



(2) Asynchronous Firing Activity



Experiment 2 performed a within-ear, between-electrode comparison of ECAPs and of synchronised measures of the brainstem (Electrically-evoked Auditory Brainstem Response, EABR) and thalamic/cortical responses (Electrically evoked Steady State response (EASSR), Cortical Onset Response, and Cortical Offset Response).

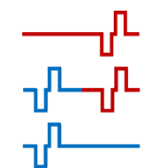
We asked:

1. **Why do ECAPs differ markedly between equally-loud stimuli?**
2. **Can we identify an objective measure that reliably produces similar responses for equally loud stimuli presented to different electrodes, while accurately reflecting the change in loudness with increasing level?**
3. **To what extent do the across-electrode variations in the different objective measures correlate with each other?**

Experiment I

STIMULI & METHOD We hypothesized that if discrepancies between perceived loudness and ECAP amplitude can be attributed to variation along the cochlea in (i) refractory properties or (ii) asynchronous firing, then ECAP amplitudes from equal-loudness stimuli should be less variable along the length of the cochlea when using the (i) Alternating-Polarity (AP) artefact-reduction technique and/or (ii) pseudo-monophasic anodic (PSA) stimulating pulses (we expect these to produce more synchronous firing by preferentially stimulating the central axon; Undurraga et al 2013) than when using the Forward-Masking (FM) artefact reduction technique with symmetric stimulation. We measured ECAPs at MCL on all electrodes for 11 users of Advanced Bionics devices in three stimulating conditions:

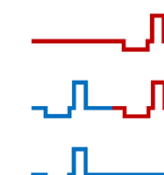
Sym_FM: Symmetric, cathodic-leading, biphasic current pulses using the forward-masking artefact-reduction technique



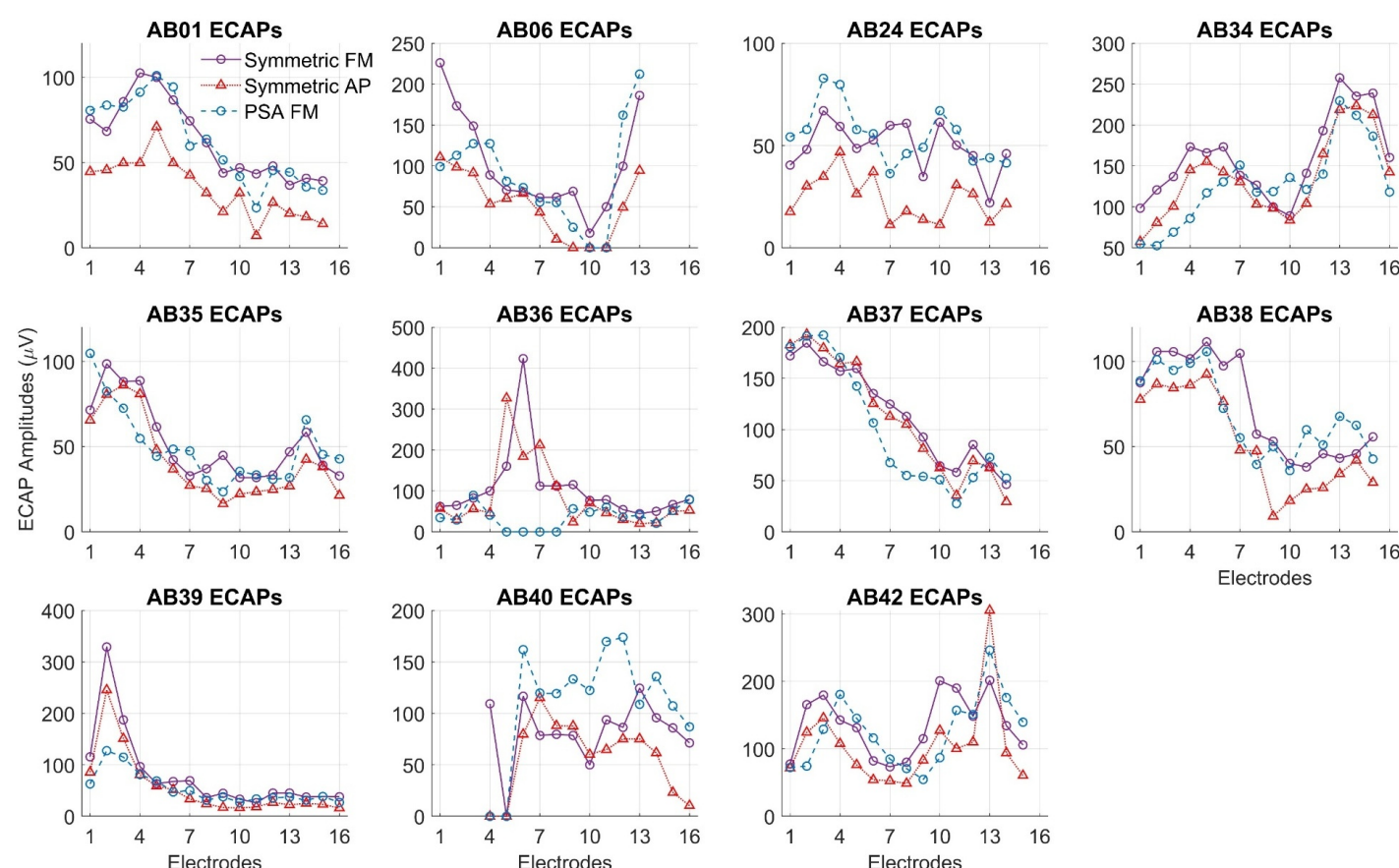
Sym_AP: Symmetric, cathodic-leading, biphasic current pulses using the alternating-polarity artefact-reduction technique



PSA_FM: Pseudo-monophasic, anodic-dominant pulses with a cathodic-leading long, low-current phase followed by a short, high-current anodic phase



RESULTS (1) ECAP amplitudes correlated significantly across electrodes between the Sym_FM and Sym_AP conditions ($r(162) = 0.77$, $p < 0.0001$; Fig 2), and also correlated significantly across electrodes between Sym_FM and PSA_FM conditions ($r(162) = 0.49$, $p < 0.0001$). The correlation between Sym_FM and Sym_AP was significantly stronger than the one between Sym_FM and PSA_FM ($p < 0.0001$). Repeated measures of the Sym_FM condition showed a significant correlation ($r(132) = 0.94$, $p < 0.0001$), and was significantly stronger than both Sym_FM ~ Sym_AP correlation ($p < 0.0001$) and the Sym_FM ~ PSA_FM correlation ($p < 0.0001$).



Data Figure 1. ECAP Amplitudes by electrode the 11 participants. The solid purple lines with circles represent the Sym_FM stimulation, dotted red lines with triangles represent Sym_AP stimulation, and dashed blue lines with circles represent PSA_FM stimulation.

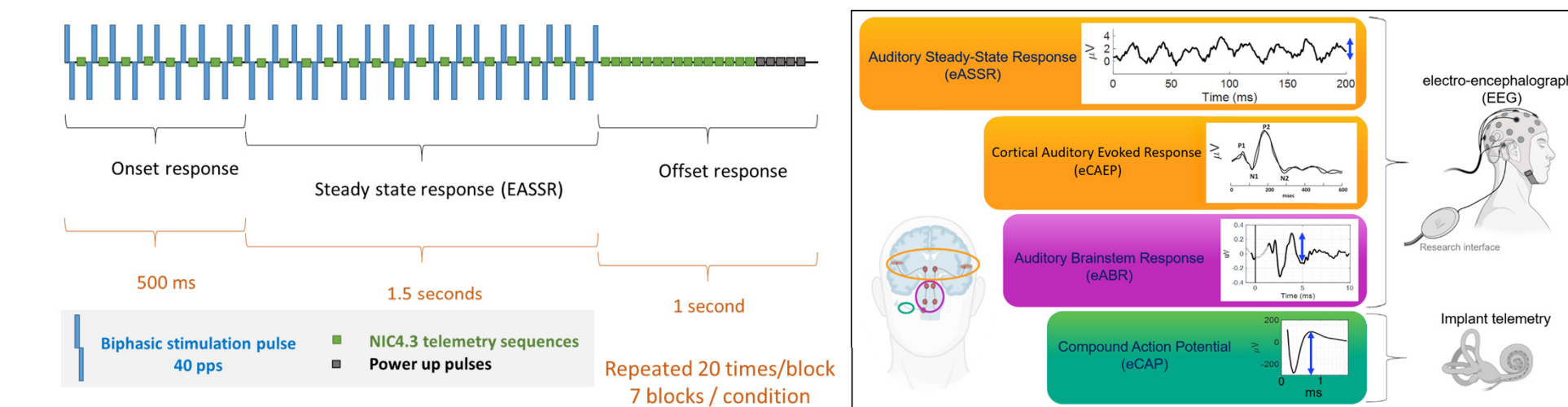
RESULTS (2)

- Between-electrode standard deviation of ECAP amplitudes between electrodes did not differ significantly between any of the three conditions (Kruskal-Wallis One-Way ANOVA $\chi^2(2) = 0.25$, $p = 0.88$)
- The current required to achieve MCL (dB re. 1 µA) was between 1.50 - 2.03 dB lower for the PSA_FM condition than for the symmetric conditions (Univariate ANOVA: $F(1,137) = 864.32$, $p < 0.0001$)

Experiment II

STIMULI & METHOD

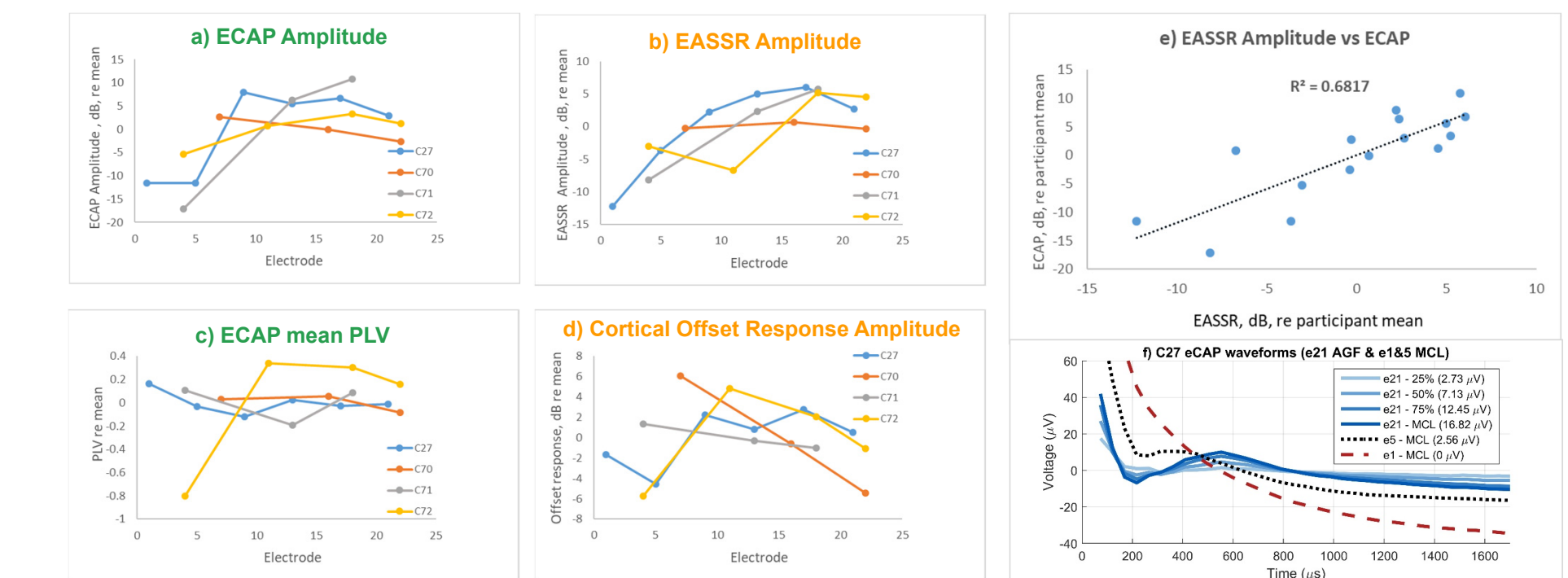
- ECAPs, EABRs, EASSRs, and the cortical Onset and Offset responses measured **simultaneously**, to the **same** stimuli:



- Pilot data from 4 Cochlear CI users
- At least 3 electrodes per participant, loudness-balanced to MCL (monopolar stimulation, 40 pps, **alternating polarity**)
- One electrode also measured at -25%, 25%, 50%, 75% of dynamic range (DR)
 - For this electrode, also measured at MCL @ 37 & 43 pps to confirm cortical/thalamic group delay for EASSRs
- ECAP: data from individual sweeps collected using reverse telemetry (NIC 4.3, Cochlear Ltd)
- EEG system used: 8-channel hyper-rate (262 kHz) BioSemi system. Montage used for data presented here = Iz vs Cz

RESULTS

- ECAP amplitudes, ECAP Phase Locking Value (He et al, 2024), EASSR, and Cortical Offset responses all produced monotonic, reliable amplitude-growth functions.
- Some Cortical Onset responses were confounded by artefact at low levels. Some EABRs were confounded by facial nerve stimulation. Analysis of these responses is ongoing.
- All measures showed considerable across-electrode variation at equal loudness (Fig. 2a-d, f)
- EASSRs captured marked across-electrode variations in ECAP amplitude ($r = 0.83$, $p = 0.0001$) (Fig. 2e). Interestingly, no correlation was observed between ECAP amplitude and PLV across electrodes ($r = 0.046$, $p = 0.87$; not pictured).



Data Figure 2. a)-d). Variation in response amplitude across electrodes for the ECAP amplitude, EASSR amplitude, ECAP PLV, and Cortical Offset response. All responses expressed re the mean for each participant. e) Between-electrode correlation between EASSR and ECAP amplitudes, expressed re mean for each participant. f) ECAP waveforms for participant C27. Solid blue lines: e21 AGF. Note that electrodes 1 (red dashed line) and 5 (black dotted line) show no/small ECAPs even at 100% of the Dynamic Range.

Summary & Discussion

SUMMARY

- No evidence that across-electrode ECAP variation is due to refractoriness or to synchrony (cathodic stimulation producing jittered responses that contribute to loudness but not ECAP)
- We can simultaneously to record ECAPs (amplitude and PLV), EASSRs, and Cortical offsets using same stimuli
- Doing so reveals that EASSRs correlate highly with across-electrode variations in ECAPs
- Perhaps surprisingly, the across-electrode variation in ECAP PLV does not correlate with the variation in ECAP amplitude.
- All measures show across-electrode variation at equal loudness

DISCUSSION

- Warning!! Experiment 2 is very preliminary (N=4)!**
- In principle, across-electrode co-variation between measures could be due to residual errors in loudness balancing. However some electrodes produce no/small ECAPs and EASSRs at 100% DR, whereas others do so at 50% DR (Fig. 2f)
- Place/frequency specific loudness compensation, occurring at a site central to our measures?
- The EASSR~ECAP Amplitude correlation is reminiscent of between-participant correlation in dynamic ranges for the 2 measures (Arzounian et al, 2025)
- Future plans include comparing these measures to onset responses obtained with higher-rate pulse trains & advanced methods (e.g. Mao et al, 2019)

Acknowledgements

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