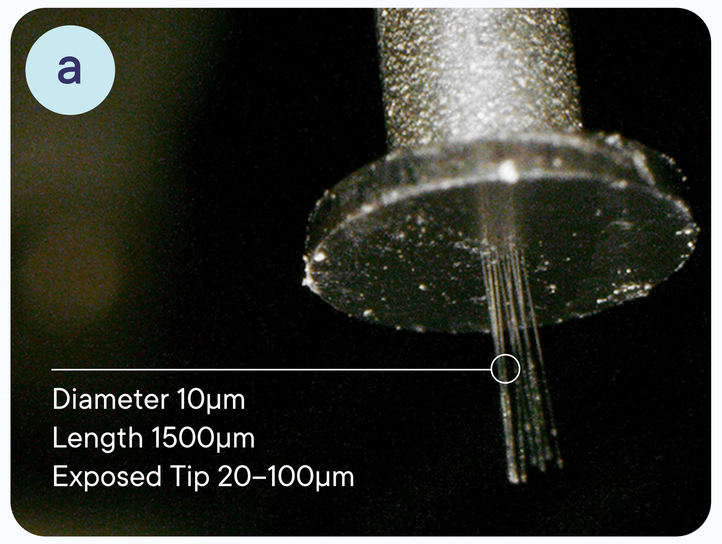
Modelling of Intracortical Neuronal Recording

Rana Jaylani & Sian McConchie | Supervised by Sorel De Leon Vergara

Carbon Cybernetics | RMIT UNIVERSITY

Introduction 1

Carbon Cybernetics are developing carbon-fiber intracortical implants with improved biocompatibility (a), but predictive tools for their recording performance are limited. Signal fidelity is strongly influenced by electrode geometry and placement, yet 3D geometries (such as carbon fibers) remain largely uncharacterised. This study developed a computational framework to better predict 3D electrode behaviour *in vivo*.



PROJECT SUMMARY

This study uses a hybrid NEURON-COMSOL FEM framework to build a predictive tool for performance of 3D cylindrical electrode geometries *in vivo*.

Methodology 2

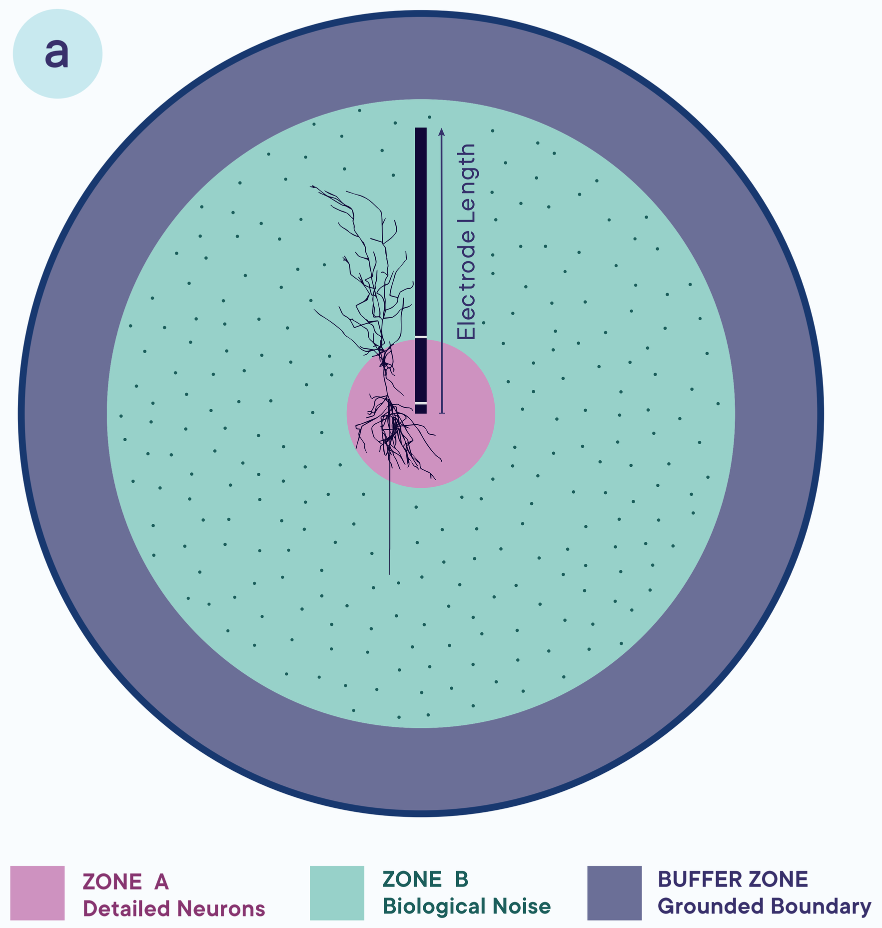
The following methodological phases were undertaken

1. Research
2. Basic Simulation Setup
3. Spatial + Parameter Variation
4. Boundary Conditions
5. Benchtop Experimentation
6. Realistic Neuron
7. Biological + Thermal Noise
8. Compiling Model
9. Analysis

Semester 1
Mid-Year Break
Semester 2

Full Scale Model (a)

A dual-zoned model was used to simulate biological noise efficiently. Neurons near the electrode were modeled in detail, while distant populations were simplified as point sources, balancing realism and computational efficiency.



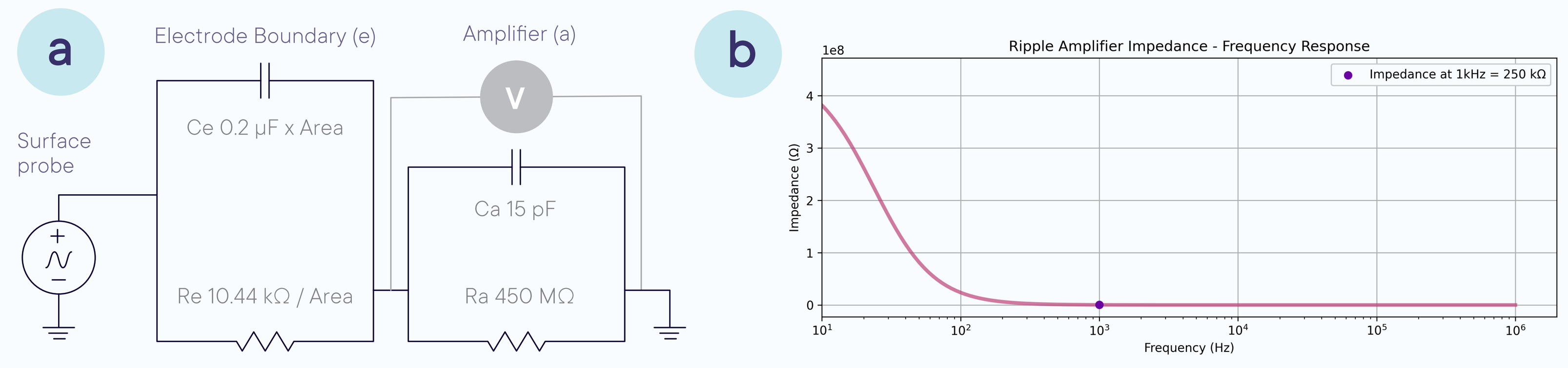
Model Build Automation

Model generation was automated through a hybrid NEURON–FEM workflow. Currents from NEURON and biological noise signals were extracted and recompiled in COMSOL via MATLAB Livelink, supporting scalable and reproducible simulations.

Results 3

Boundary Conditions

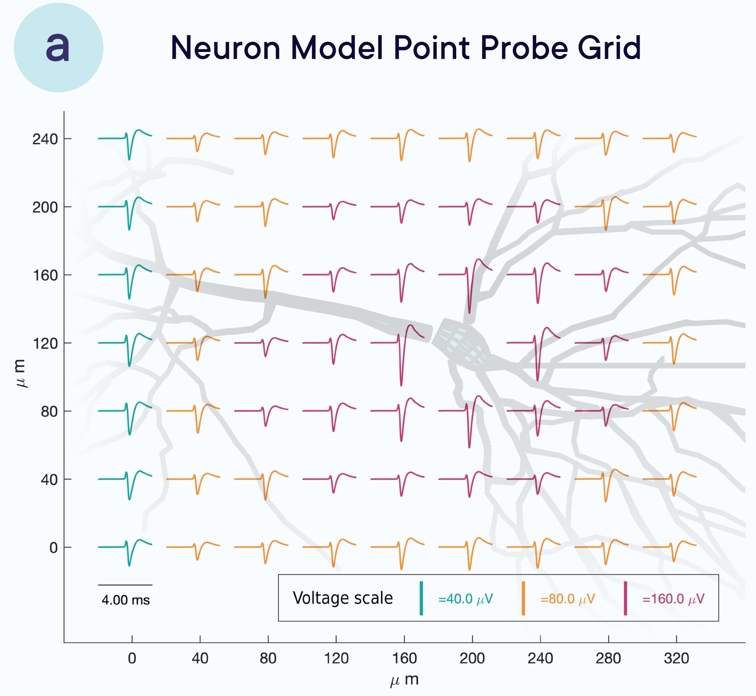
Randles circuit was implemented to model electrode-tissue interactions & amplifier effects.

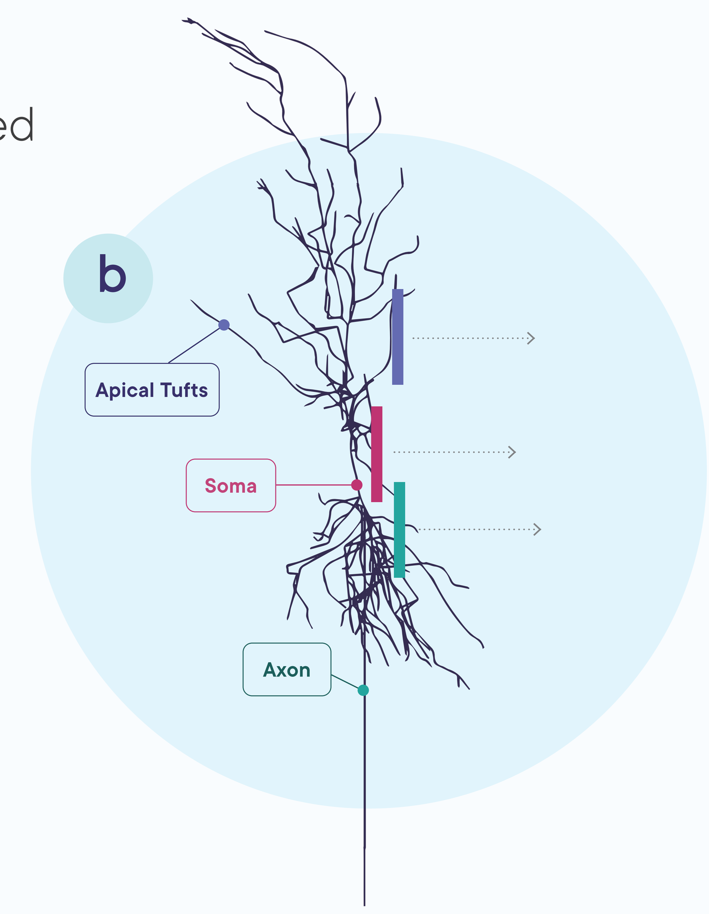


a) Randles circuit implemented in COMSOL. b) Frequency response of simulated electrode.

Single Neuron

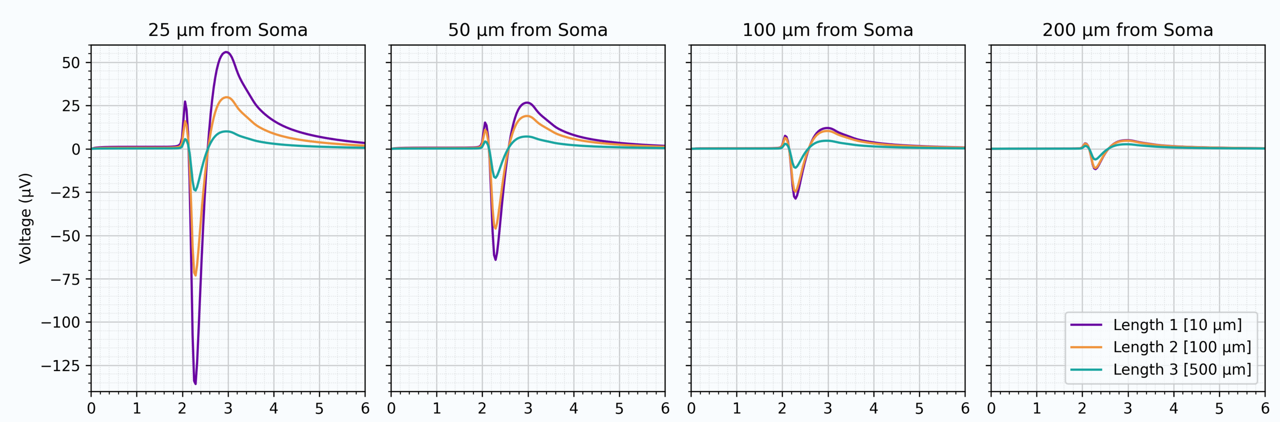
A realistic neuron morphology and corresponding membrane currents [2] were generated in NEURON and imported into COMSOL as line-source currents.



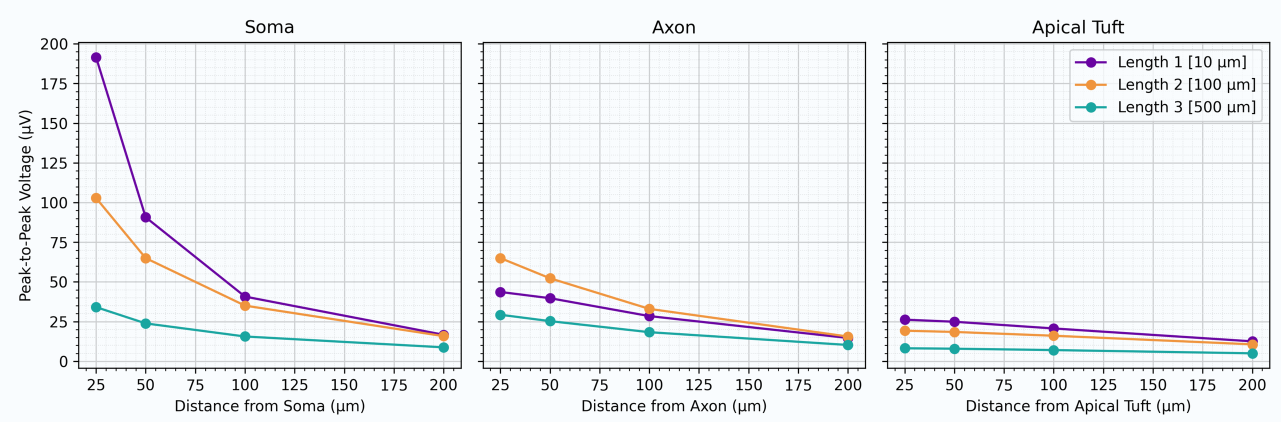


a) Point probe results were consistent with the neuron source literature. [2]

b) Electrode placement relative to neuronal compartments for parameter sweeps.



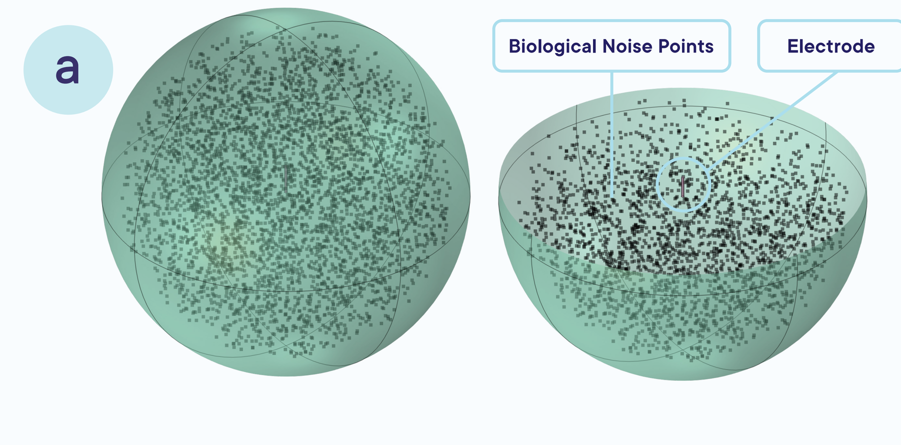
c) Small electrodes have the highest magnitude advantage close to the soma.



d) As distance increases (>50 µm), amplitudes of small and medium lengths converge.

Noise

Noise amplitude decreases with increasing electrode size, as larger electrodes average over a greater surface area.



b $S_v(f)=4k_B\,T{\cdot}R(Z(f))$

a) Biological noise was simulated by assigning experimentally recorded spike waveforms to point neurons firing at realistic rates.

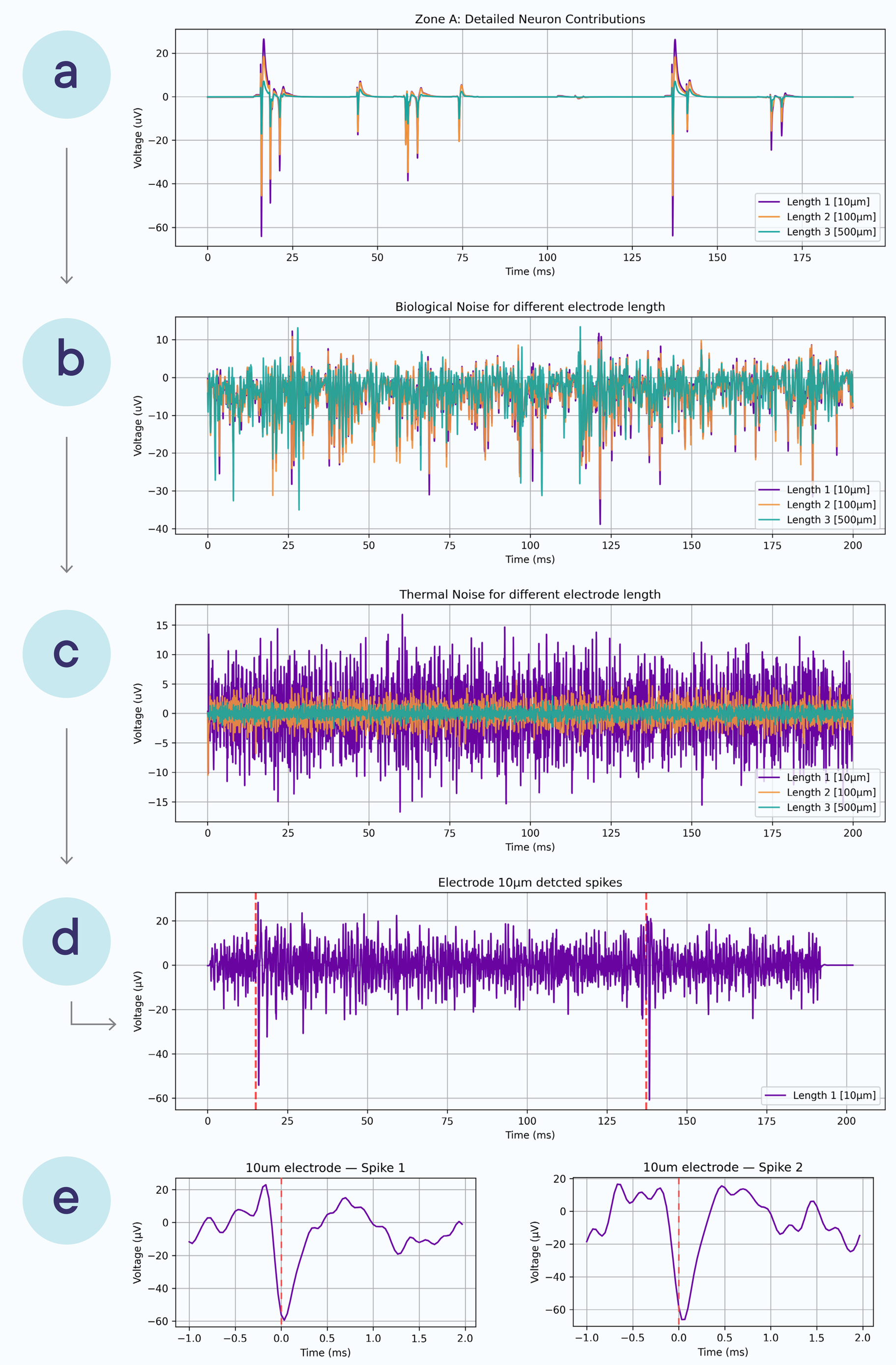
b) RMS thermal noise calculated from electrode impedance.

Full Model

Recordings from individual neurons in Zone A **(a)**, biological noise in Zone B **(b)** and thermal noise **(c)** were were combined using superposition **(d)** to replicate realistic intracortical recordings.

Electrode Length	SNR (V/V)	Performance Summary
10 µm	5.46	Largest spikes, clear single-neuron resolution
100 µm	5.33	Slightly smaller spikes, still resolves single neurons
500 µm	3.74	Lower resolution, captures combined activity

Table 1. Signal-to-noise ratio and key performance insights from full-scale model.



e) Two spikes from the target neuron were detected for 10 µm, shown-side-by-side. Additionally, 100 µm electrodes detected the same two spikes, while the 500 µm length detected a different spike.

Discussion 4

- √ COMSOL–NEURON model accurately captured intracortical electric fields.
- √ Length and distance impacted signal fidelity.
- √ 10 µm displayed a high amplitude near soma, 100 µm struck the best SNR balance while 500 µm produced broad but weak signals.
- √ MATLAB LiveLink workflow enabled fast, flexible, and reproducible simulations for neural interface design and optimisation.
- x Further optimisation of time-dependent study parameters in COMSOL are needed to address computational limitations.

[1] L. A. Camuñas-Mesa and R. Q. Quiroga, "A Detailed and Fast Model of Extracellular Recordings," Neural Comput., vol. 5, no. 5, pp. 1191–1212, May 2013, doi: 10.1162/NECO_a_00433.

[2] C. Gold, D. A. Henze, C. Koch, and G. Buzsáki, "On the Origin of the Extracellular Action Potential Waveform: A Modeling Study," J. Neurophysiol., vol. 95, no. 5, pp. 3113–3128, May 2006, doi: 10.1152/jn.00979.2005.