DESIGN OF A PORTABLE ELECTROENCEPHALOGRAM SYSTEM: BRAIN-COMPUTER-INTERFACE GAMING AS A PROOF-OF-CONCEPT

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With thanks to the team at AGENDA

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Aims of the Project

Large numbers of people living in rural areas and less developed countries currently have little or no access to epilepsy treatment. A key component of the treatment pathway is diagnosis by electroencephalogram (EEG): however, existing clinical systems are highly expensive and require significant infrastructure (i.e. a hospital).

This project aims to investigate the feasibility of alternative EEG technologies, and develop a fully integrated, portable EEG prototype that can bring diagnostic capability to these underserved regions. Covid-19 prevented a formal study in the intended user groups and lack of laboratory access, so the performance of prototypes was constrained to existing off-the-shelf systems and methods, such as a BCI video game controller that measures brain rhythms. The game serves as a proxy for use-cases, serves as an educational tool, and highlights the challenges of designing a diagnostic pipeline.

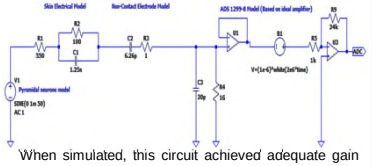
AGENDA

Accelerating solutions for **G**lobal **E**pilepsy with **N**ovel **D**iagnostics and **A**pps (AGENDA) is an Oxford University study, lead by Arjune Sen and Sloan Mahone, that seeks to "help reduce gaps in knowledge, diagnosis, treatment and safety for people with epilepsy in resource poor nations". This project forms the hardware portion of AGENDA. The study is running in 5 countries: Kenya, Zimbabwe, South Africa, India and Brazil.

Novel non-contact electrode concept

Both Ag/AgCl and dry electrodes require contact with the skin, so are blocked by thick layers of hair. This isn't ideal for AGENDA, as hair types in the target settings tend to be thicker and more tightly curled.

A non-contact electrode can be created that uses a capacitor, rather than a resistor, to pick up the voltage from the scalp. This would function through hair and clothing, making it ideal for AGENDA. The circuit diagram for such a system is shown below.



When simulated, this circuit achieved adequate gain over the frequency range of interest (1 – 100 Hz). However, the signal to noise ratio can fall to 0.34 dB depending on the separation between the scalp and the electrode plate. Following the work of Sullivan *et al.* [4], reducing the high noise power created by the non-contact electrode – for example, by using an active shielding plate – is the next key step in implementing this technology.

Background: Target Settings

- **50 million** live with epilepsy worldwide [1]
- Up to **70% (35 million)** could live seizure-free if diagnosed and treated
- **80% (40 million)** live in low-middle income countries (LMICs)
- Of those, **75% (30 million)** don't get effective medical treatment or diagnosis
- In 2015, epilepsy cost **168** Quality-Adjusted Life Years (QALYs) per 100,000 people [2]
- There is a lack of neurological specialists in these countries: Zimbabwe only has **2** full-time neurologists in a country of **14.65 million**
- Across LMICs, 60% of the population lives in rural areas with little access to hospitals or clinics [3]

Background: EEG types in Current Usage

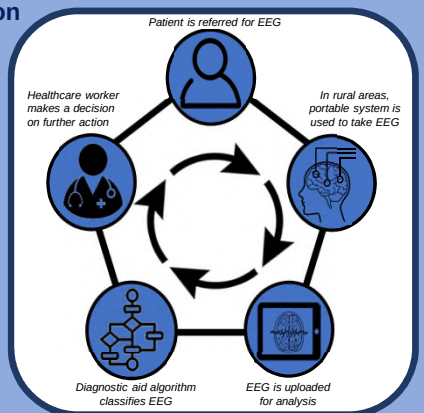
Current clinical standard is to use silver electrodes with a chloride releasing electrolytic gel ("Ag/AgCl electrodes"). Ag/AgCl electrodes can achieve impedances as low as 10 kΩ, so introduce the least noise into the signal.

These must be applied separately by hand, by a trained clinician, to ensure they're located correctly. The gel also causes irritation if left on the skin, so needs to be washed off with clean water after the recording.

Consumer devices and gaming systems often use "dry electrodes", where a metal (often stainless steel) probe is held in contact with the scalp. The contact impedance is typically around 50 kΩ, meaning the signal-to-noise ratio is lower than for Ag/AgCl.

Dry electrodes don't need any consumables, such as gel, to function and require less maintenance. They are also built into a headset or headband, lowering the application time significantly (at the cost of losing some ability to customise the fit to an individual's head). Unlike Ag/AgCl electrodes, the contact impedance relies only on how tight the fit is: the impedance figure shows, correctly fitting the electrodes can reduce their impedance by a factor of 32.

In general, an acceptable impedance for EEG is below 100 kΩ for modern amplifiers (>100 MΩ input impedance).



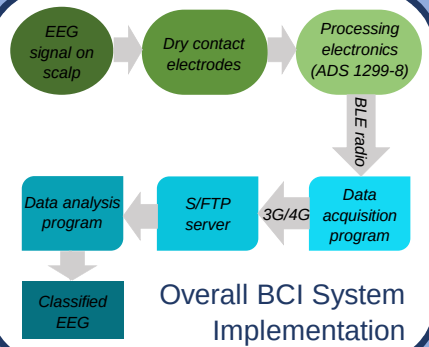
OpenBCI Ultracortex Headset

The Ultracortex headset is a 3D-printed, 16 channel EEG system using dry electrodes useful for gaming applications. It operates from battery power, and connects to a computer using Bluetooth. Due to its low cost, portability and ease of development, this headset was evaluated as an option for the AGENDA prototype EEG system.

The dry electrode, in a screw-spring housing. Prongs are 2 mm.

The OpenBCI headset in use. Image from OpenBCI.

Assessment using a video game pipeline helped illustrate limitations of the technology. For example, the electrodes are screw tightened, which can lead to hair being caught in the electrode prongs and preventing a good contact. This is especially evident for people with longer hair: in the impedance figure, subject 2 had much longer hair than 1 or 3, and showed a much lower reduction in impedance after fitting the electrodes. A solution to the issue may be to use electrodes with longer (>5 mm) prongs, or switch to an alternative such as non-contact electrodes.



Overall BCI System Implementation

Field Use

The AGENDA system needs to be operable by users who are not specialists in performing or interpreting EEG.

The system is capable of using a test signal to measure the impedance at each electrode. This helps the user to ensure a proper fit across all channels.

The data analysis can be done fully remotely, with an email of results being sent to the healthcare worker for follow-up. The diagnostic algorithm developed by Ines Pont-Sanchis is meant to aid decision making by a human, rather than be a replacement.

Acknowledgements

This project would not have been possible without the help and support of Tim Denison and Moaad Benjaber, both of whom were extremely generous with their time. Thanks as well to Charles Newton, Sloan Mahone, Farrah Mateen, Elisaveta Sokolov and Gaynor Foster for giving their time in interviews, as well as to Ines Pont-Sanchis for her excellent work on the AGENDA classifier.

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[2] GBD 2015 Neurological Disorders Collaborator Group, "Global, regional, and national burden of neurological disorders during 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015", in *Global Health Metrics*, pp. 877-897, 2017
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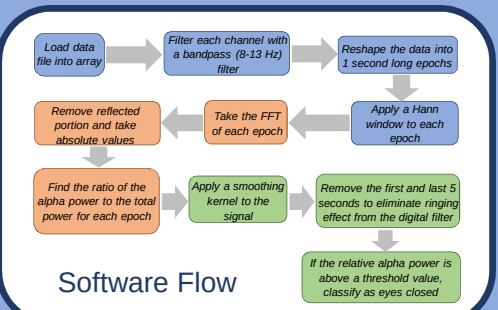
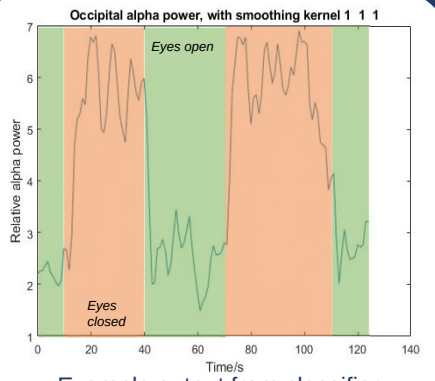
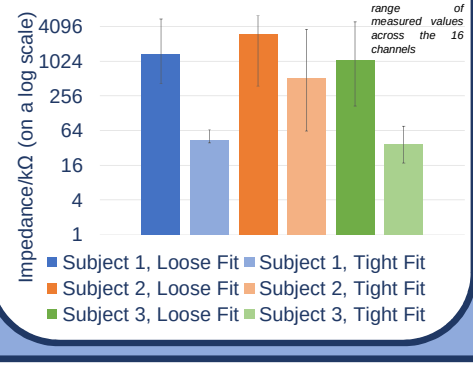


Software Flow



Example output from classifier

Electrode Contact Impedance Change Due To Fitting

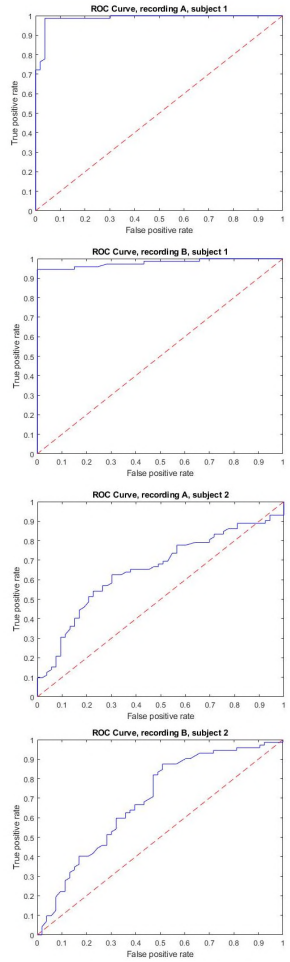


Conclusions

An analysis of available EEG technology was taken, with dry electrodes being chosen as the most suitable for the specific requirements of AGENDA. The dry electrode contact is used on video gaming hardware today, and an existing device was evaluated using a video game as a proxy for AGENDA's final use case. Practical issues such as dry electrodes being challenged by thick hair was noted. A novel technology, non-contact capacitive electrodes, was simulated and found to be a potential replacement pending lab testing and further refinement. A prototype pipeline was built using an OpenBCI video game headset as a hardware base. To demonstrate its functionality, a typical gaming signal of alpha band power was measured and then classified to determine when their eyes were closed or open. The system was demonstrated to offer an improvement over chance in all tests performed, although it performed better on those with short hair.

BCI Game Signal: Proxy and Metrics

To test the reliability and quality of the data taken from the headset, a known metric was needed. When awake but resting, eye state correlates heavily with the relative signal power in the "alpha band" – between 8 and 12 Hz. Closed eyes increase the power at these frequencies. This signal is a characteristic used in gaming applications, and representative of the final epilepsy application A simple automated classifier was designed to take the raw recording and detect when the eyes were open or closed, to prove the system provides sufficient data quality for a classifier to work with. The software flow diagram shows how the program works. ROC Curves are provided below for two subjects. Subject 2 had a much greater contact impedance due to their thicker hair, which correlates well with the expectation that thick hair is a major impediment to acquiring good quality data even for games.



For an ROC curve, the ideal classifier is vertical from (0,0) to (1,0), then horizontal. The red line represents random chance.