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Wearable neurotechnology for inferring the driver's attention for assistive driving

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FINAL RESEARCH REPORT

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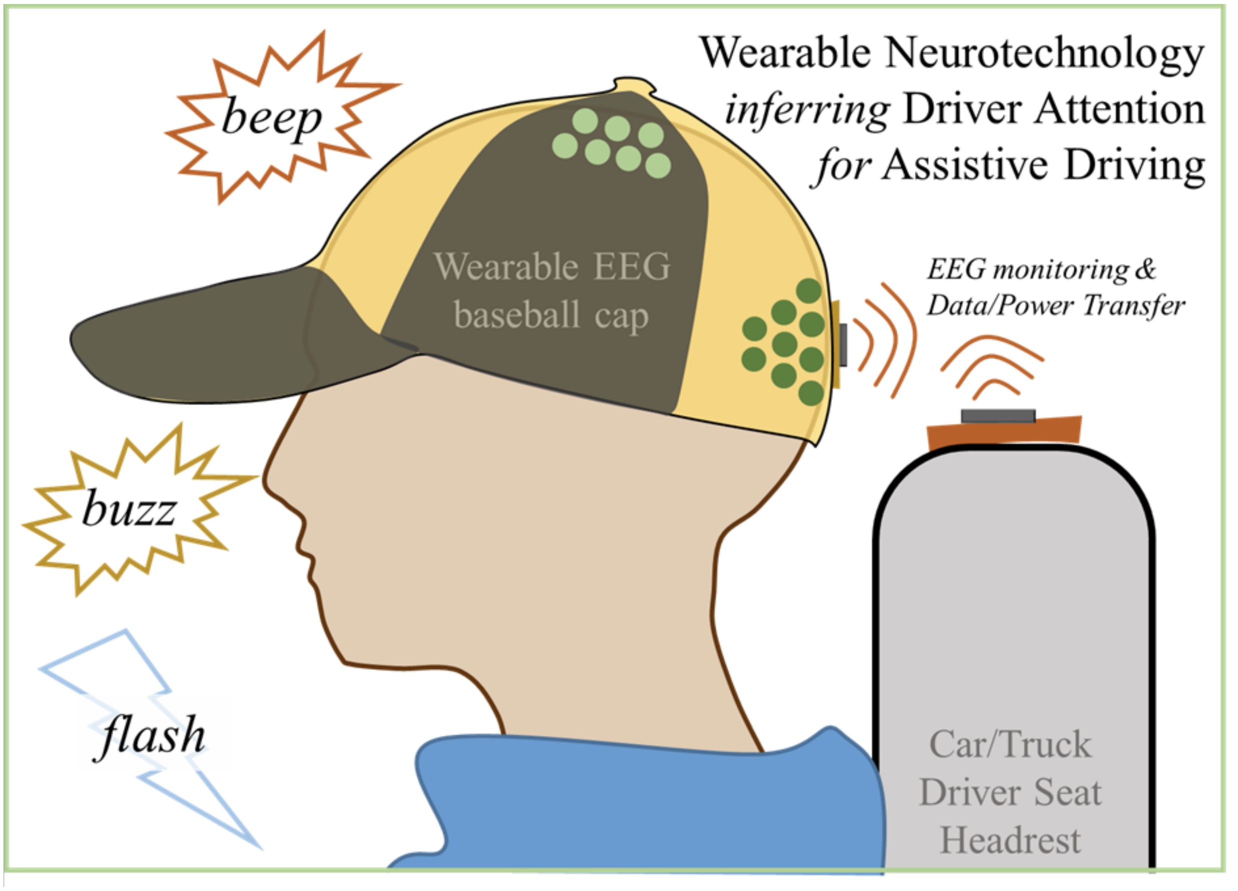


Overall vision: Easy to apply EEG that can be work in cars by everyone, that can reliably detect attention as well as adverse events (such as epileptic seizures), aiding the driving and making it more accessible for people suffering from attentional disorders or epilepsy.

Prior work and what's new: The work builds on our prior works[1–3], on instrumenting electrocephalography (EEG) systems that are accessible and quick and comfortable to apply. Supported by Mobility21, the systems were improved and new recordings were acquired at UPMC Children's hospital as well as locally in our lab. This is what is described in this report. In doing so, we partnered with Precision Neuroscopics, Inc., a Pittsburgh startup that helped us advance our ideas and results. We were, however, unable to test these systems using neuroscience experiments for decoding attention because of reduced ability to do experiments with COVID-related lockdowns. In our view, this is acceptable, as many other works show that EEG signals are able to decode attention reliably (for both visual and auditory attention, see, e.g. [4,5]).

The problem: EEG systems are bulky and difficult to install, and do not work with all hair-types. Hence, the focus of our work over the past year has been on making EEG easy to install (**Quick-apply, long-term use EEG**), and to make it work with all hair-types (**Accessible EEG**).

1. **Accessible EEG**: **Preliminary Data and Metrics for EEG Quality.**
   Methodology: Most studies with new EEG electrodes[6–8] only observe classic signatures (e.g. electrode-scalp impedance, alpha waves, visual examination of the power spectrum). We identified signal quality using 9 EEG metrics to ensure clinical utility:

1. **Fraction of electrodes with acceptable impedance:** What fraction of electrodes have impedance smaller than 50kΩ for > 95% time (without maintenance or adjustment of electrodes)?
2. **"ERP Core"-based quantification.** We leverage Kappenman and Luck's initial work on quality assessment of EEG based on required number of trials to attain statistically significant differences in Event-Related Potentials (ERPs) known to evoke different brain responses[6], and subsequent work[9] on ERP-Core which also offers techniques and representative data for EEG SNR quantification. Using these, we aimed to quantify for each electrode type (and, when needed, with and without braiding), the quality of EEG signals. E.g. more noisy electrodes require a larger number of trials for a statistically significant difference for stimuli that evoke different responses.
3. **Fraction of EEG recording with acceptable data:** EEG technologists and experts will grade data-quality based on visual examination of time-traces, quantifying how many time-frames of data have acceptable quality, and how many electrodes have acceptable recordings.
4. **Alpha peak over surrounding frequencies**: Visual examination of the peak in the alpha-band power over surrounding frequencies, on log-scale. How distinguishable is the peak when eyes are closed, and is it larger statistically than when eyes are open? This will be done under a resting-state experiment, with eyes open and eyes closed (for 1 min each).

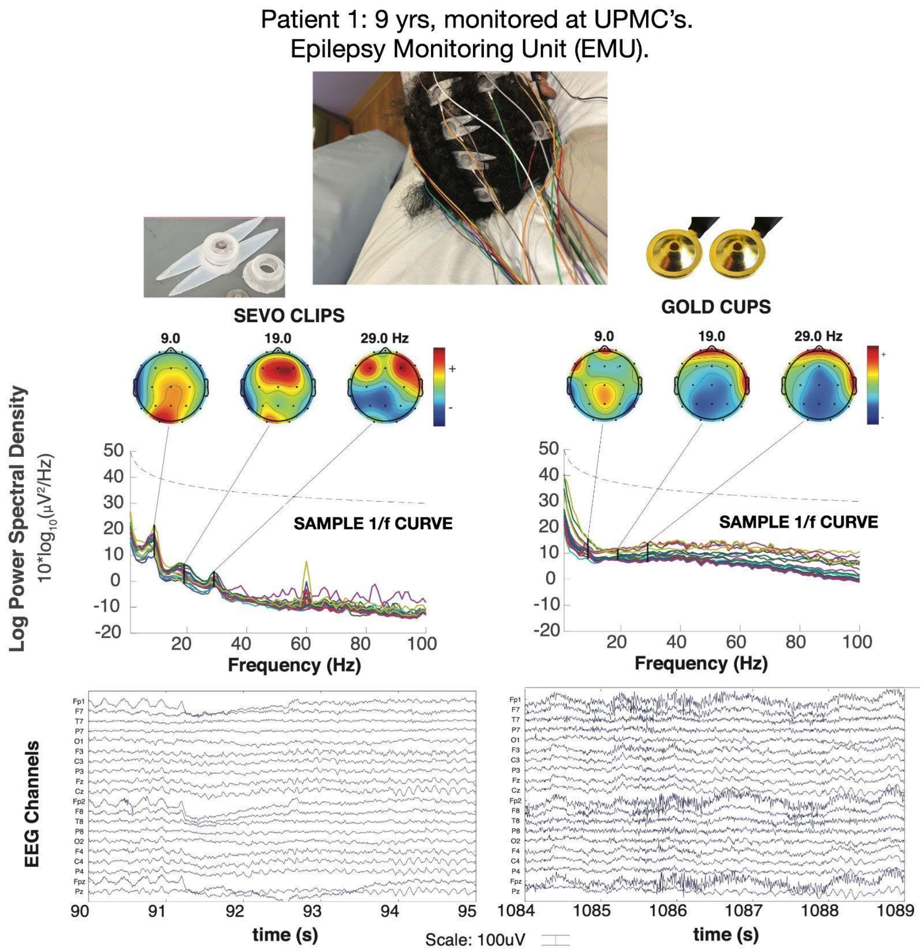


Fig. 1. Our preliminary data on one of two patients suspected of epilepsy recorded during their hospital visit for epilepsy screening. The data was recorded *after braiding,* which exposed the scalp, in the clinical 10-20 arrangement using classic gold-cup electrodes and Sevo electrodes. The figure shows illustrative samples to show that, in **Metrics 3, 4, 5, and 6**, Sevo electrodes dramatically outperform clinical gold-cup electrodes. In **Metric 1**, our prior work [Etienne et al.'20] already showed that Sevo electrodes outperform gold-cup electrodes.

5. **1/f decay**: Until what frequency does the spectrum decay as 1/f? A relevant work that will guide our efforts here is Donoghue et al.[10]. If large white noise is present, 1/f decay will stop at a lower frequency.
6. **Localization of activity in expected region: a) Alpha power:** Does alpha power localize in occipital region when eyes are closed? **b) Localization in active sensory tasks:** Does auditory and visual stimulation create large activity where most expected (e.g., temporal and occipital regions)?

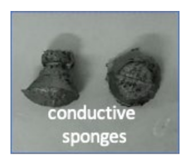
7. **Stability of statistics**: How does the stability of the signal statistics (e.g. drift of EEG mean, variance, power in frequency bands, across time) compare across different systems?
8. **Only for healthy participants: Power spectral metrics: SSAEP/SSVEP:** Amount of time required with SSVEP/SSAEP for statistically significant increase in the frequency of presentation and its harmonics. Harmonics have lower power and higher frequency, thus providing additional information to quantify SNR at more than one frequency.
9. **Only for epilepsy patients: Detection of signatures of epilepsy**: Is there significant improvement in the ability to detect signatures of epilepsy using Sevo electrodes, as judged by clinical EEG techs?

Our goal is to design electrodes that outperform (with statistical significance) the state-of-the-art in no less than 6 of these metrics, and not perform worse in any of them.

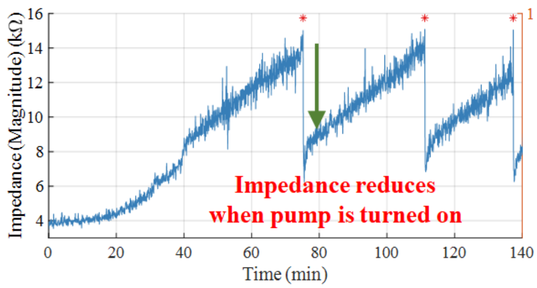
Preliminary data and findings: Preliminary data was recorded on two epilepsy patients at UPMC Children's Hospital, by our collaborator Dr. Christina Patterson. As Fig. 1 discusses, Sevo electrodes, in pilot testing and/or in our neuroscientific testing, outperform gold-cup electrodes even with braiding in Metrics 1, 3, 4, 5 and 6 (and have not yet been tested for other metrics).

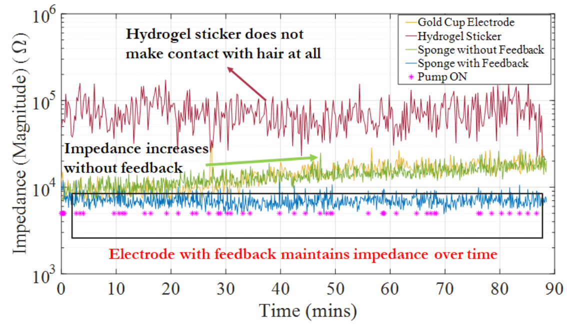
Conclusions: It is now evident that current EEG systems do not work for all hair-types, and it is encouraging to see that our new EEG systems (Sevo) are able to improve performance over clinical grade systems. We firmly believe that more improvements are needed to have systems work as well for coarse and curly hair as for other hair-types. We still need to understand if this has clinical implications on seizure detection, which is a part of our ongoing efforts.

2. Quick apply, long-term use EEG: The work in this task builds on our team's breakthrough success in improving wearability of EEG. We were able to build conductive-sponge-based EEG modules that enable **perpetual Sensing with Conductive Sponges**. When state-of-the-art wet electrodes dry out over prolonged use (>2 hours), the electrode-skin impedance increases to unacceptably high values, degrading EEG signal quality. Our work has developed a new material that ensures a low electrode-skin impedance regardless of the wetness of the interface. This material is a "conductive sponge" (illustrated on the right) that is embedded with conductive carbon nanofibers (CNFs).[2,11] When infused with saline, the sponge provides a conductive medium between the electrode and the skin. More importantly, the ***carbon fibers make the sponge conductive even when it is dry***. We also demonstrated that as the percentage of carbon fiber increases, conductivity (when dry) also increases.



In the work funded by Mobility21, we demonstrated that the electrode-skin impedance can be kept low for long periods of time by automated rehydration of electrodes based on measurement of impedance. The feedback system (figure on the right) releases a small amount of water/saline when high impedance is detected, lowering the impedance (see figures below) and, thereby, reducing maintenance effort.





Preliminary findings: Impedance was kept low for several hours. More experiments are needed for publication.

Conclusions: Our systems can keep EEG signal quality good for several hours, and could be instrumented to be easy to apply and comfortable to wear, once the form-factor for the rehydration system is reduced.

Publications: The results are in preparation for submission to journals. No publications have appeared yet from the work done under Mobility21.

Data: We are unable to share the data as it was acquired clinically, and the necessary permissions for sharing are not with us.

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