Mini-Symposia Title:

Methods for trustworthy and reliable in-the-wild EEG recordings

Mini-Symposia Organizer Name & Affiliation:

Alex Casson, University of Manchester, UK

Mini-Symposia Speaker Name & Affiliation 1:

Alex Casson, University of Manchester, UK

Mini-Symposia Speaker Name & Affiliation 2:

W. David Hairston, US Army Research Lab

Mini-Symposia Speaker Name & Affiliation 3:

Arnd Meiser, Carl von Ossietzky University of Oldenburg, Germany

Mini-Symposia Speaker Name & Affiliation 4:

Ashwati Krishnan, Carnegie Mellon University

S Mini-Symposia Speaker Name & Affiliation 5:

Mini-Symposia Speaker Name & Affiliation 6:

- ( ) 01. Biomedical Signal Processing
- ( ) 02. Biomedical Imaging and Image Processing
- ( ) 03. Micro/ Nano-bioengineering; Cellular/ Tissue Engineering &
- ( ) 04. Computational Systems & Synthetic Biology; Multiscale modeling
- ( ) 05. Cardiovascular and Respiratory Systems Engineering
- (•) 06. Neural and Rehabilitation Engineering
- ( ) 07. Biomedical Sensors and Wearable Systems
- ( ) 08. Biorobotics and Biomechanics
- ( ) 09. Therapeutic & Diagnostic Systems and Technologies
- ( ) 10. Biomedical & Health Informatics
- ( ) 11. Biomedical Engineering Education and Society
- ( ) 12. Translational Engineering for Healthcare Innovation and Commercialization

Mini-Symposia Synopsis— Max 2000 Characters

Electroencephalography (EEG) is the monitoring of a subject's 'brainwaves' by placing electrodes on the scalp, and is of key use for non-invasive brain interfacing. However, typical EEG signals are very small (micro-Volts) and very easily corrupted by artefacts. Historically collecting high quality signals outside of highly controlled laboratory environments has been extremely challenging.

Overcoming these challenges necessitates highly multi-disciplinary work between system designers for long battery life electronics, signal processing engineers for artefact robust signal collection and analysis, electrode designers for easy-application systems, and neuroscientists to integrate properly with fundamental research. We propose a session to span these areas and highlight recent developments fostering the state-of-the-art in out-of-the-lab EEG. This will continue a series of sessions at EMBC since 2008:
• 2008: Towards truly wearable electroencephalography
• 2011: Reliable and trustworthy physiological signal monitoring in daily-life
• 2013: EEG monitoring brought to home: what have we achieved and the road forward
• 2016: Next generation electroencephalography recording electrodes
• 2018: Next steps in real-life brain monitoring: technologies for wearable EEG
This series has created a strong EMBC community, in a timely manner aligning with the IEEE Brain initiative.

For this year's session we propose a focus on methods for assessing EEG electrodes and units. Even something as basic as a clear definition of signal-to-noise ratio is not clear in EEG measurements, and the interaction between the electrode-body

Theme:

Speaker 1 Synopsis

Alexander J. Casson, University of Manchester, UK

***Abstract*— The verification of in-the-wild EEG, where many motion artifacts are present, is intrinsically very challenging as there is no ground truth of "correct" data available in order to determine whether artifact removal techniques have been successful. Nevertheless, having confidence that good quality EEG signals are being collected is extremely important as EEG studies begin to transition out of the lab. This talk will overview how multiple verification techniques can be explored at the same time to build confidence in the overall level of performance. This will cover the development of our EEG head phantom, the use of machine learning verification techniques, and lessons learned from simultaneous EEG+motion measurements.**

I. Bio

Dr Alex Casson is a Reader (Associate Professor) in the Materials, Devices and Systems division of the Department of Electrical and Electronic Engineering at the University of Manchester. His research focuses on non-invasive bioelectronic interfaces: the design and application of wearable sensors, 'conformal sensors' for human body monitoring, and data analysis from highly artefact prone naturalistic situations. This work is highly multi-disciplinary and he has research expertise in:

- Ultra low power microelectronic circuit design (at the discrete and fully custom microchip levels).
- Sensor signal processing for power constrained motion artefact rich environments.
- Personalised device manufacture using 3D printing and inkjet printing.

He has particular interests in precision devices for closed loop bioelectronic interventions: those which are tailored to the individual by personalised manufacturing via printing; and tailored interventions by adjusting stimulation parameters using data driven responses/outputs from real-time signal processing. Dr Casson's ultra low power sensor work is mainly for health and wellness applications, with a strong background in EEG and transcranial current stimulation. These applications focus on both mental health situations including epilepsy, sleep disorders, stroke, Parkinson's disease and autism, and physical health/rehabilitation applications including diabetic foot ulceration.

Dr Casson gained his undergraduate degree from the University of Oxford in 2006 where he read Engineering Science specialising in Electronic Engineering (MEng). He completed his PhD from Imperial College London in 2010, winning the prize for best doctoral thesis in electrical and electronic engineering. Dr Casson worked as a research associate and research fellow at Imperial College until 2013 when he joined the faculty at the University of Manchester. He is an ambassador for the Manchester Integrating Medicine and Innovative Technology (MIMIT) scheme for systematically connecting clinicians and engineers to address unmet clinical needs. Dr Casson is currently a Senior Member of the IEEE, Fellow of the Higher Education Academy, and chair of the Institution of Engineering and Technology's healthcare technologies network.

A. J. Casson is with the Department of Electrical and Electronic Engineering, The University of Manchester, Manchester, UK; e-mail: alex.casson@manchester.ac.uk.

II. Talk Synopsis

This talk will overview three complementary avenues we have been investigating for controlled EEG unit evaluation and testing. It will build upon our recently published review in this area [1].

Firstly we will overview our use of gelatin head phantoms which allow a *known* EEG signal to be played out and recorded. This allows comparison of the recorded and the actual EEG signal in a way which is not possible with on-person tests. We have been performing experiments on different head phantom mixtures, and how the materials used control the electrical properties of the phantom, and how these properties change over time.

Secondly, we will overview our use of machine learning approaches for verifying whether artefacts have been removed from the EEG signal successfully. In on-person measurements no measurement of the true EEG present is possible, making it difficult to know whether artefacts have been successfully (or completely removed). We suggest that if machine learning cannot differentiate between artifact free and artifact cleaned sections of EEG data, this helps build confidence that the artifact removal process has been successful.

Finally, we will discuss concurrent measurements of EEG and motion using IMU sensors. The inclusion of a gyroscope is important, and our results suggest that EEG recordings are much more sensitive to angular movements, as measured by the gyroscope, than to linear acceleration components as measured by an accelerometer.

References

[1] A. J. Casson, "Wearable EEG and beyond," Biomedical Engineering Letters, vol. 9, no. 1, pp. 53–71, 2019.

Speaker 2 Synopsis

W. David Hairston, US Army Research Lab

***Abstract*— Many new types and designs of EEG electrodes and retaining systems have been developed to facilitate so-called "real world neuroimaging". However, motion-related artifacts remain a problem, and to date, there is no accepted method for objectively quantifying the susceptibility of a specific material or design to artifacts. In this talk, I describe efforts to design next-generation phantom substrates and models used as a surrogate for human scalp for this purpose, as well as methods ongoing in our lab to validate the relationship between phantoms and real skin. Examples are given based on conventional wet and new generation dry electrodes.**

I. Bio

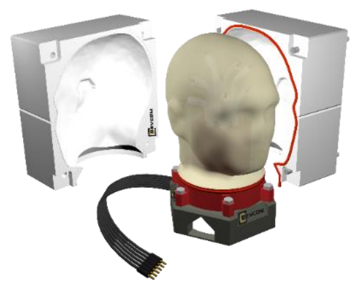
W. David Hairston is a staff neuroscientist for the US Army Research Laboratory (ARL) in the Real-World soldier Quantification branch. As part of the Human Research and Engineering Directorate, he leads their research program on "Real-World Neuroimaging" (RWN), which aims to move neuroscience outside of the lab to improve human-system interactions. He has been a Science area Lead for the Cognition and Neuroergonomics Collaborative Technology alliance since 2009. Aside from developing novel neurotechnologies and de-noising approaches, much of his work addresses the challenge of establishing community-adopted methods for validating new approaches.

II. Talk Synopsis

Many new methods for "dry" EEG are particularly prone to motion artifacts, especially when used in real-world scenarios. It is therefore necessary to have an objective method for evaluating the artifact susceptibility of any putative new material or design in order to assess its potential usability. Unfortunately, traditional human subjects-based comparisons are ill-posed for this situation due to their variability and lack of a ground truth baseline.

In this talk, I will describe our lab's efforts to derive reliable phantom head surrogates which replace the human as a test fixture, in order to provide a repeatable basis of comparison, and validate it and show some examples with varying types of electrodes. Notably, in order to be useful, a proper phantom must have the necessary conductive properties, and at least approximately similar artifact behavior, to match what is observed in human skin.

Phantom head models are created using the design currently released under the Open EEG Phantom Project (https://osf.io/qrka2/). For applications requiring an internal signal, a multi-dipole model is used, which has several internal multi-poled antenna in an internal tree-like structure. Projects focused solely on motion artifact susceptibility, which require more of a solid structure but no dipoles, use an alternative model based a rigid head-shaped "skull" that is FDM printed with a 1cm layer of surrounding conductive medium. For the conductive medium, previous work has used Vise ballistics gel with NaCl and gel powder wt % varied to tune the conductive properties. Ongoing work is exploring varied mixtures of agarose and NaCl, which is more stable at room temperature, to mimic skin-like artifact properties.



To validate the phantom, human subjects walk on a treadmill in conjunction with a Vicon motion capture system while wearing various COTS gel and dry EEG systems. Motion profiles are then recreated using a 6-dof motion platform with a phantom head model attached, with the phantom wearing the same COTS systems. Additionally EIS with the phantom materials and electrodes provides assessment of the conductive noise and signal transfer.

To date, data show that ballistics gel can easily be conductively "tuned", with the best concentration around 0.9% NaCl and up to 35 wt % concentration to match the skin conductance. However, we find the gross scale of artifact in realistic motion to be dramatically lower than observed in humans, likely due to the low charge transfer resistance at the electrode junction. Instead, agarose gelatin appears a better choice when used with only ~0.2% NaCl concentration. Meanwhile, we have shown that with this phantom method we can quantifiably compare the base SNR, charge transfer resistance, noise frequency profile, and artifact resettling time constant for multiple types of dry and wet electrodes.

We advocate phantom devices for validating the efficacy of new electrodes or other EEG DAQ approaches, and interactions with ionic-to-electronic conductor transfer. Additionally, when used with a motion platform, they provide a baseline for motion artifact removal methods. They can also be used to characterize environmental noise and assess methods for removal of EMI from data.

W. D. Hairston is with the US Army Combat Capabilities Development Command Army Research Lab, Aberdeen Proving Ground, Maryland, 21005; phone: 410-278-5925; e-mail: William.d.hairston4.civ@mail.mil.

Speaker 3 Synopsis

Arnd Meiser, Carl von Ossietzky University of Oldenburg, Germany

***Abstract*— Measuring EEG "in the wild" using ear-EEG makes it necessary to employ methods that are different from those of a lab environment. Ear-EEG recordings come with a reduced number of electrodes positioned at unusual locations. Knowing to what kind of brain activity these innovative approaches are sensitive to is far from trivial and an empirical validation often is time consuming and financially expensive. In this talk, computational simulation of signals emitted by the brain and forward modeling from the source to the recording electrodes will be discussed. Throughout the talk, forward modeling will be presented as a way to shed light on what sources can be captured with a certain electrode setting. In addition, the influence of inter-individual differences in brain anatomy will be discussed. The comparison between the cEEGrid and traditional full cap EEG can be used to determine what limitations and what advantages we can expect when measuring in real life situations.**

I. Bio

Arnd Meiser received his Master's degree in 2019 from the University of Oldenburg in Cognitive Neuropsychology. Currently he is a PhD student in the Department of Psychology at the Carl von Ossietzky University of Oldenburg, Germany. He works in the "Neurophysiology of everyday life" group of Martin G. Bleichner. His research focuses on understanding the sensor–source relationship of around-the-ear EEG recordings. To gain a better understanding which neural sources ear-EEG electrodes are sensitive to he uses source modeling (forward and inverse). His work aims to advance the field of mobile ear-EEG, both by determining the optimal electrode positioning and by taking inter-individual differences in brain structure into account.

II. Talk synopsis

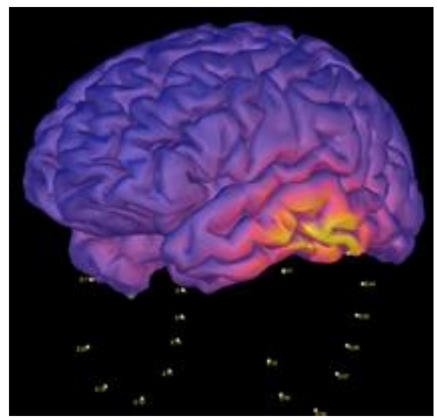
This talk will focus on the application of forward modeling for estimating the sensitivity of specified electrode settings (namely the cEEGrid [1]) to sources in the brain.

In the first part, an approach for simulating sources will be presented. Their forward models and topographies, including the recorded signal on the electrode sites will be discussed. A comparison between the standard high-density EEG-cap and the cEEGrid, which comes with a lower spatial coverage, but also with a better applicability in real life situations, will be made. Alternative electrode setups will be considered, including a recent publication advancing the technique of in-ear-EEG with forward modeling [2] to show the relevance of shape and placement of the cEEGrid in measuring auditory signals.

The second part of the talk will be concerned with the underlying factors that contribute to sources being more or less detectable with the cEEGrid and tie up to the distribution of the cEEGrid electrodes. This part will also include a brief outlook of what factors have to be additionally included for modeling signal detection in the future.

Finally, I will discuss the role of the individual brain anatomy on the recorded signal. Due to differences in cortical folding, the signal that originates within a specific anatomical structure may be reflected differently on the scalp level. Integrating folding and connectivity of the cortex into the placement of the few electrodes available is therefore beneficial for maximizing the signal amplitude.

I will discuss how to account for these interindividual differences when interpreting ear-EEG data.



Shown above is the result of the forward modeling of multiple simulated sources to the cEEGrid. For every point on the cortex mesh, the activity of that point was set to 1 while the rest was set to 0. From the resulting signal arriving at the cEEGrid, the electrode pair measuring the highest amplitude was found. The corresponding value was then back-projected onto the mesh grid. The result is a sensitivity map for the cEEGrid with yellow indicating the maximum amplitude, blue indicating the minimum. While this is a relative measure without realistic units, it can be seen that sources in the temporal lobe are better recognized than those in the surrounding areas.

References

[1] Bleichner, M. G., & Debener, S. (2017). Concealed, Unobtrusive Ear-Centered EEG Acquisition: cEEGrids for Transparent EEG. Frontiers in Human Neuroscience, 11(April), 1–14. https://doi.org/10.3389/fnhum.2017.00163

[2] Kappel, S. L., Makeig, S., & Kidmose, P. (2019). Ear-EEG Forward Models: Improved Head-Models for Ear-EEG. Frontiers in Neuroscience, 13(September). https://doi.org/10.3389/fnins.2019.00943

Speaker 6 Synopsis

Ashwati Krishnan, Carnegie Mellon University, Pittsburgh, USA

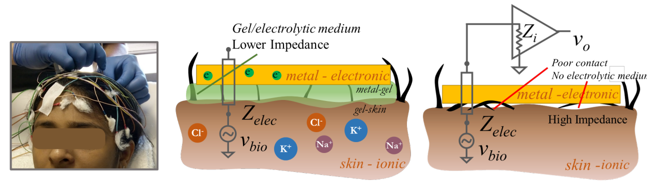
***Abstract*— There have been significant developments in EEG technology in the last two decades, including new sensor materials and various styles of EEG caps. However, many of these technologies are not adopted for large-scale use, and clinicians today rely on standard tools of gold cup electrodes and conductive gels for EEG sensing. The reasons we have identified are fundamental, individually placed wet electrodes provide a more reliable signal to noise ratio, even though they are cumbersome to setup. Commercial EEG caps cannot be fit on different hair styles and types, causing bias in patient experience. In view of all these issues, we have developed a hydrophilic conductive sponge material, along with electrode clips and methods that fit coarse and curly hair types. Our goal is to ensure an inclusive approach to the design of new-generation EEG devices.**

I. Bio

Dr. Ashwati Krishnan is a research engineer who has studied neuromodulation techniques for the last decade. She completed her Ph.D. at Carnegie Mellon University in Pittsburgh where she developed safe electrical stimulation techniques and circuits for retinal prosthesis devices. Her post-doctoral work involved the development of systems for high-density EEG [1], where she invented novel sensor materials and electrode designs for EEG measurements. Along with her research students, she has identified that current EEG technology does not work with participants who have coarse and curly hair, thereby noticing a systemic bias in the design of EEG devices. Together, they have introduced engineering solutions towards a more inclusive EEG measurement system. Her contributions allow for quick application, low-cost and accessible EEG measurements.

II. Synopsis

Biopotential measurements such as electromyography (EMG) and electroencephalography (EEG) have high spatial frequency components that can give us more insight into the function and transportation of signals in the body. However, a fundamental bottleneck preventing reliable electrical measurements of the human body is the interface between the electrode and the skin. Clinical-grade sensors that measure electrical signals from the body almost always have an electrode coupled with an electrolyte gel or hydrogel. These gels allow the transfer of ions between the electrode and skin that result in low impedance interfaces. Technicians who install EEG systems for epilepsy monitoring undergo a painstaking routine to ensure that gel electrodes placed on patients' heads have low impedance. A few major problems exist in the practical usage of these gels: (i) they are viscous and sticky, making them cumbersome to apply and remove; (ii) they dry out and become non-conductive, rendering the recording useless (iii) they have long setup times, about 40 minutes for 19-23 electrodes.



(a) Clinical Gel EEG *(b) Wet Electrode Impedance < Dry Electrode Impedance*

Fig. 1. *(a)* Typical clinical application of wet electrodes in an EEG clinic *(b)* Illustration of dry versus wet electrodes on skin.

A solution to the practical problems with wet electrodes has been the development of dry electrodes. Dry electrodes rely heavily on contact with the skin and usually need to be active electrodes. Because the skin is ionic, a sensor which can support ionic charge transport will fundamentally always perform better than a dry electrode. Medical institutions therefore continue to use only wet electrode measurements for critical signals, even for low density EEG.

In this talk, I will describe a novel solution for a quick application, wet and dry electrode sensing system. Our electrodes comprise a *hydrophilic*, *conductive* sponge material that uses saline to form easy-to-apply wet skin contact that *remains conductive* even as the electrode dries [2]. Another aspect that I will cover is the fact that current EEG technology does not work well for people with coarse and curly hair, typical for those of African descent [3]. One of our lead researchers, Arnelle Etienne identified this issue, and we believe it to be a very serious flaw in the approach of medical device design. We have developed a unique method of braiding and electrode design (Sevo) that allows for improved scalp contact and prolonged use of electrodes. When combined with the hydrophilic, conductive sponge electrodes, the Sevo electrodes are a low-cost, quick application, accessible design that makes EEG more inclusive to the community.

References

[1] A. Krishnan, R. Kumar, A. Etienne, A. Robinson, S. K. Kelly, M. Behrmann, M. Tarr, and P. Grover, "Challenges and opportunities in instrumentation and use of high-density EEG for underserved regions," *EAI Second International Conference on Innovations and Interdisciplinary Solutions for Underserved Areas*, Aug. 2018.

[2] A. Krishnan, K. Rozylowicz, S. K. Kelly, and P. Grover, "Hydrophilic conductive sponge sensors for fast setup, low impedance bio-potential measurements," *42nd Annual Conference of the IEEE Engineering in Medicine and Biology Society*, Aug. 2020.

[3] A. Etienne, T. Laroia, H. Weigle, A. Afelin, S. K. Kelly, A. Krishnan, and P. Grover, "Novel electrodes for reliable eeg recordings on coarse and curly hair," *42nd Annual Conference of the IEEE Engineering in Medicine and Biology Society*, Aug. 2020.