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Wearables and the Brain

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The brain is the last frontier for wearable sensing. Commercially available wearables can monitor your vital signs and physical activity, but few have the ability to monitor what goes on inside your head. With the advent of new wearable and portable neuroimaging technologies, this situation might be about to change, with profound implications for neuroscience and for wearables.

One of the main attractions of wearables, and wearable sensing, comes from the proximity of the devices to the human body and to the wealth of information that might be gathered from being so close. Yet when it comes to sensing the brain – and, even more so, our minds – significant difficulties arise. First among these is the inadequacy of available sensing technology. It is relatively easy to sense the movement of a person's arm, but much more difficult to gain access to the workings of their brain. Secondly, and perhaps more fundamentally, we still do not really know enough about how brains actually work in the real-world and outside the restrained laboratory setting – and it is hard to sense and make use of what we do not quite understand.

Despite the difficulties, there are things we can do to help us understand, and make use of, the signals from this most complex organ and its workings – both as engineers, by building better sensing methods, and as neuroscientists, by improving experimental design. Wearables have an increasingly important role in these activities. Here we give a short overview of current brain imaging technologies, and the challenges involved with using these, with a particular emphasis on their applicability as wearables. We then discuss how wearable sensing can help transform our understanding of the brain through improved, more ecologically-valid neuroscience.

SENSING METHODS

EEG

Electrodes that measure brain activity have been widely used (and abused) ever since the time of Richard Caton (1842-1926), who first measured brain signals in live animals. Electroencephalograph (EEG) is an aggregated trace of neural spiking patterns, and is measured as a voltage drawn between pairs of electrodes placed at key locations across the scalp [8]. Certain frequencies and locations of EEG are known correlates of particular cognitive states, such as the tendency of alpha waves (8-12 Hz) to become suppressed when a person is concentrating (and active when asleep). EEG is fast and can give valuable information on brain changes within tens of milliseconds. The hardware needed to sense and process EEG is cheap, and easily integrated into a wearable (e.g., see the NeurotechX project https://neurotechx.com). This is particularly useful for building technology that can detect (and act on) epileptic seizures, for example, and has been marketed as an input device for gaming.

Several downsides to EEG exist, however. A low signal-to-noise ratio (SNR) means EEG is sensitive to electrical interference from other sources, like musculature, heart rate, or electrical devices. EEG is heavily affected by movement, even by blinking, and this can make it difficult to use in a wearable and naturalistic context. A further downside to EEG is that, although fast, electrical damping through the skull limits its spatial resolution (to around 5-9 cm).

MEG

The electrical signals of different brain regions can also be measured by detecting the weak magnetic fields that they create. This is the approach used in magnetic encephalography (MEG). The main advantage of MEG is its improved spatial acuity compared to EEG, while retaining a fast temporal response. However, in order to capture these weak signals, interference from other sources, like the earth's magnetic field, need to be cancelled out. Typically, this can only be done in a magnetically sealed chamber with a controllable field coil. And, until recently, MEG sensing apparatus relied on super-cooled components that could only be used in a specialised, and expensive, laboratory. These result in very large one-size-fits-all MEG scanners to accommodate the bulky cooling system. A further constraint of MEG is that participants have no scope for movement, with their heads being clamped in place during experiments.

With all of these constraints, this technology is not one that comes to mind when considering wearable sensing. Recently, however, researchers developed a radical new sensing system that removes most of the bulky apparatus and opens up the possibility of `wearable' MEG sensing during free movement. As yet the system requires a shielded room and field coil to counter the Earth's magnetic field, and head movement is limited to no more than 50 cm, but it is conceivable that these issues might be overcome with further research [1].

MRI AND fMRI

The predominant non-invasive method for scanning the brain (and the body, generally) is magnetic resonance imaging (MRI). This, exclusively lab-based, method uses a strong magnetic field and targeted radio-waves to detect minute differences in the composition of water molecules throughout the whole brain. From this, MRI can be used to create spatially accurate 3D images of the brain's structure.

Functional MRI (fMRI) expands on this, and has been instrumental in helping neuroscientists to explore the dynamics of brain function [5]. Rather than measuring the brain electrical activity like EEG or MEG, fMRI looks at the oversupply of blood flow to the brain to meet the neurons' demand for oxygen during brain activity. This means that the more active a particular region of the brain, the higher the concentration of oxygen-carrying molecules in the supporting blood vessels to that region. The varying concentrations of oxygenated and deoxygenated haemoglobin (HbO_2 or HbR) are measured by analysing proton spin differences under fMRI. The resulting hemodynamic response is known as the blood-oxygen level dependent (or BOLD) signal. However, the relationship between brain activation and BOLD is not instant, with delays of up to 4-6 seconds between activation and measurement.

Like MEG, fMRI imposes restrictions on participant movement, requiring those being scanned to lie still with their head trapped in a narrow (and noisy) tube. This makes it difficult to study, e.g., neurodevelopment, as infants will require sedation. The strong magnetic fields also make fMRI unusable for people with metal or electronic implants, and make it hard to integrate with other devices for multimodal monitoring. This limits the ecological validity of fMRI-based studies, particularly when studying questions related to, e.g., natural human behaviour.

fNIRS

Besides fMRI, brain hemodynamics can also be monitored using optical techniques, like functional near-infrared spectroscopy (fNIRS) [10]. fNIRS shines the brain with near infrared (NIR) light (650-950 nm) and measures the changes in concentration of HbO_2 and HbR, taking advantage of their different light absorption properties. Using relatively cheap NIR sources and light detectors placed on the scalp, fNIRS can measure the BOLD signal across the outer cortical regions with a good degree of spatial sensitivity (2-3 cm) by looking at the light attenuation by the two species of haemoglobin. Although still limited by the poor temporal response of BOLD, fNIRS has the major advantage over the abovementioned neuroimaging technologies of being robust to electrical and magnetic interference, being suitable for multimodal monitoring, and allowing a degree of movement. The downside, however, is that the penetration depth of the light limits sensing only to the outer cortical regions of the brain, reaching a depth of around 1.5-2 cm.

WEARABLE fNIRS

Wearable fNIRS devices can now be bought that are cheap, lightweight, and can be worn wirelessly [9]. Systems like the LIGHTNIRS from Shimadzu (Figure 1 A) let cognitive neuroscientists do functional neuroimaging in-situ and outside the laboratory. Although laboratory-based experiments have been fundamental to advance our knowledge of the brain, real-world testing is a better model of real life than artificial lab-based computer tasks, and can increase the ecological validity of experiments. fNIRS is a powerful tool towards achieving real-world neuroscience, being robust enough to allow a wider range of body movement within different environments.

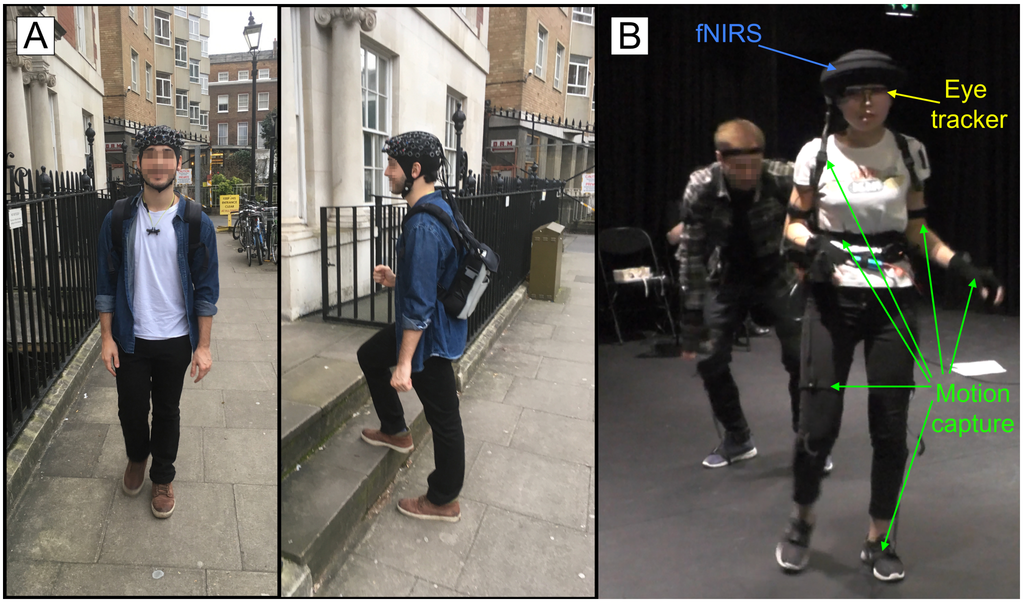

Figure 1. (A) Wearable fNIRS being used in free movement outside the laboratory (*LIGHTNIRS* manufactured by *Shimadzu*, Japan). **(B)** Actors performing while wearing wearable fNIRS (*WOT*, *Hitachi*, Japan), wearable motion capture devices (*Perception Neuron*), and eye trackers (*Pupil Labs*)

APPLICATIONS OF REAL-WORLD NEUROIMAGING

Preliminary studies have shown the feasibility of using wearable sensors to investigate basic and low-level cognitive functions in highly ecological scenarios [8]. In the coming years, exciting new applications and research using wearable brain sensing can be expected, with several fields of cognitive neuroscience set to benefit.

The social brain

One obvious field to benefit from wearables is the study of the social brain. Within this framework, neuroscientists have focused their attention on scanning multiple brains simultaneously, also known as *hyperscanning*, to investigate how different people's brains are connected to each other during social interaction. With traditional neuroimaging technologies, this could only be done by having two or more people restrained in different fMRI or MEG scanners, often isolated in different rooms and communicating via screens. Clearly, this does not reflect social interactions, where the exchange of verbal and nonverbal cues are key aspects of human communication. The situation improves when using lab-based EEG or fNIRS, but the artificial environment of the laboratory can interfere with participant's natural behaviour, and their freedom of movement can be restrictive. By moving outside the lab, the ecological validity of such scenarios would increase enormously, and we would have the opportunity to explore the real neural mechanisms that underlie and support human social interactions as they happen in the real life.

Training and development

Educational neuroscience is another field set to benefit from wearable brain scanning. Several scanners might be worn by students in a classroom to monitor their (different) learning processes. This could provide the foundations to new theories of learning, guiding new educational interventions, developing personalized learning strategies to fit each student, and adapting teaching formats to meet each child's need throughout their brain development.

A similar post-hoc analysis can be applied to brain signals recorded from airline pilots with the aim of helping to improve in-flight procedures. Recent work demonstrated the viability of using fNIRS and EEG to analyse the cognitive performance of pilots as they performed difficult manoeuvres while in training simulators [3].

Clinical uses

It is worth mentioning the clinical implications of wearable neuroimaging. Wearable sensing might be used to monitor the brain integrity of elderly people and, for instance, be used together with cognitive training techniques to reduce and delay age-related cognitive decline. Neurofeedback training systems that use wearable brain sensors can be used by people suffering from neurological and neurodevelopmental conditions. For example, children with attention deficit hyperactivity disorder (ADHD) could use neurofeedback to adjust their brain activity patterns and re-focus their attention. In a similar way, children with autism spectrum condition (ASC) might use this technology to improve their social awareness and communication skills by learning to control their brain activity [2].

Brain computer interfaces

Explicit brain-computer interfaces (BCI) relies on the fact that we can be trained to control our brain activity. A person can learn to manipulate their EEG signals, for example, by adjusting their focus of attention on certain visual stimuli, or imagining physical movement [6]. Applications include direct brain control of, e.g., robots, computer games, prosthetic limbs, or as a communication channel for people with locked-in syndrome. Traditionally, EEG has been used for BCI, but because of noise and the lack of spatial discriminability of that method, researchers are starting to use fNIRS, or a combination of both [7]. This opens up the possibility of using the temporal response of EEG to detect neurological changes in real time, with fNIRS then used to help enhance the precision of a specific classification.

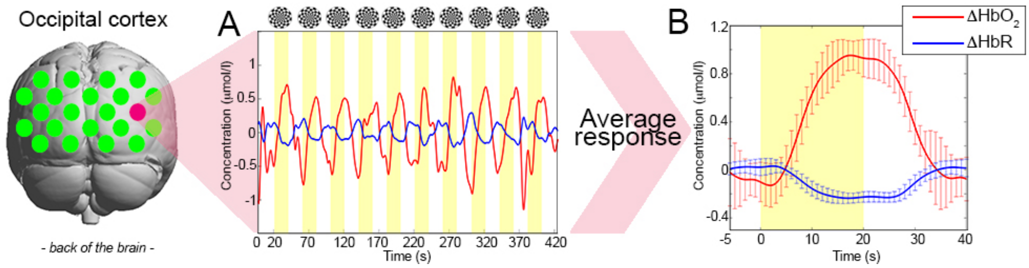

Figure 2. Example of fNIRS data (HbO_2 in red and HbR in blue) from 22 measurement points (green and magenta dots) on the occipital cortex during a visual stimulation task using a flashing checkerboard. Panel A shows an example of fNIRS time series during the visual stimulation (yellow areas). Panel B shows the averaged HbO_2 and HbR signals (mean ± standard deviation) across 10 repetitions.

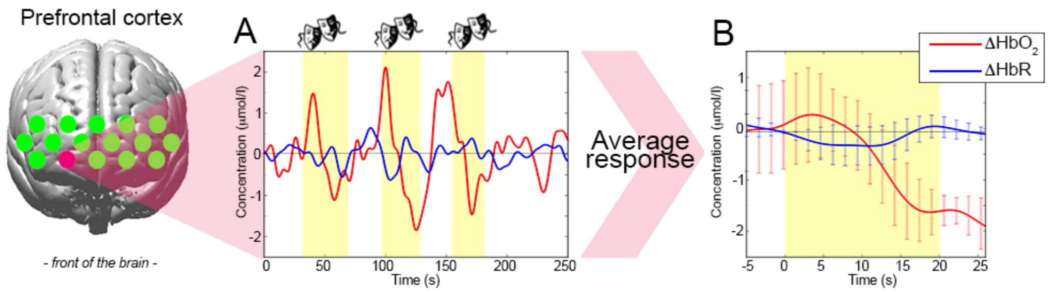

Figure 3. fNIRS data from the prefrontal cortex during a social interaction task. Panel A shows HbO_2 and HbR time series during the 3 task blocks (yellow areas). Panel B shows the averaged signals (mean ± standard deviation) across the 3 repetitions.

CHALLENGES

The opportunities provided by brain sensing in real-world settings come with new challenges both for neuroscientists and for engineers. Experimental design methods in neuroscience need to be improved to account for real-world conditions, while at the same time technological improvements are needed to better sense and process ‘in the wild’ brain signals.

Experimental design

In a typical neuroimaging experiment, neuroscientists repeatedly present stimuli that are spaced out by a few seconds of rest, usually on a computer screen, and try to look at the changes in brain signals as an average across those repetitions. These are called block- or event-related designs and are used to improve the power of the detection of brain activity and to avoid false positives or negatives due to the noise in the recorded brain signals. This helps uncover possible correlations between sensor readings and cognitive processes.

An example of a block-designed functional experiment is shown in Figure 2. Data were recorded using a lab-based fNIRS instrument (ETG-400, Hitachi, Japan) during a visual stimulation (flashing checkerboard) activating the occipital cortex (at the back of the head). The flashing checkerboard was presented for 20 seconds (yellow areas in Figure 2) on a computer screen, alternated with 20 seconds of rest, and repeated 10 times. This experiment is specifically designed to create involuntary, low-level cognitive activations of the visual system. Note how the hemodynamic responses (i.e., increase in HbO_2 and decrease in HbR) are highly consistent and reproducible across each of the 10 blocks (Figure 2 A), resulting in a strong average response with very small variability (Figure 2 B). This is typical of what might be sensed from low-level cognitive processes, like vision or motor control, in an ideal laboratory condition using only 1 or 2 stimuli.

But with higher-level cognitive functions, like problem solving, or social cognition, the neural correlates are far more variable. Figure 3 shows an example of a channel measuring the prefrontal cortex activity during a social interaction task using a wearable fNIRS (WOT, Hitachi, Japan). Briefly, the participant performed a scene from a Shakespeare play 3 times (yellow areas in Figure 3 A) while interacting with another actor. The hemodynamic responses shown in Figure 3 A are less consistent across blocks than those of Figure 2, with more complex patterns of HbO_2 and HbR changes. This results in a highly variable average response (Figure 3 B). Because of the inconsistency of the hemodynamic changes across the repetitions, we might conclude that this task did not produce statistically significant hemodynamic changes. For this reason, cognitive experiments are designed to include a high number of stimuli repetition in order to increase the power of detecting hemodynamic changes and reduce the between-repetition variance.

One challenge for neuroscientists trying to design experiments to test real world cognitive behaviours, is that repetitive block designs are not good models of what we encounter or do in our everyday lives. Real life activities, like walking on the street, conversing, listening to music, do not happen in repetitive bursts, interspersed by fixed-time delays. Added to this, taking participants out of the lab, where distracting elements are kept to a minimum (e.g., noise-proof and isolated testing rooms), and onto the street introduces a range of unpredictable influences and obstacles, like other people, cars, etc. Regardless of whether it is from high- or low- level cognitive processes, the complexity of recorded brain signals will increase in the presence of such confounding factors. It can thus be difficult to isolate brain activity caused by whatever cognitive process is being studied from activity caused by other interferences.

Theatre as a laboratory

One approach to tackle these issues, which we have begun to explore in our own work, is to swap the laboratory for the theatre. Using `theatre as a laboratory’ we make a compromise between the degree of control of the lab and the freedom of the real-world. This environment can be controlled to reduce unwanted distractions/stimuli, while still being open-ended, and at the same time giving participants the freedom to move and behave under limited restraints. In addition to providing a conducive environment for experiments, theatre provides a ready-made mechanism for exploring human social interactions in a naturalistic and repeatable way. By having actors, who are wearing brain sensors, repeatedly rehearse scenarios involving the behaviours we would like to study, we can achieve a block-like experimental design for neuroscientific studies with far fewer constraints than traditional setups. Figure 1 (B) shows a still from a preliminary work where we demonstrate how wearable, multi-sensor recording of two actors in performance can be used to obtain usable neuroimaging data [4]. Theatre, together with wearable sensing, thus represents an intermediate step between the lab and the outside world. It provides a forum in which to explore new models and theories on how the brain functions in open-ended and naturalistic situations, and helps prepare us as we move towards more chaotic, real life neuroimaging.

Signal quality

The second major challenge is to find ways to improve the sensitivity and noise response of sensing technology. An improved SNR would help reduce the amount of stimulus repetition required in cognitive studies, as well as reduce detection errors in BCI applications.

There is a need to incorporate body sensing alongside the brain. Freely moving people create brain signal artefacts that are quite different from the ones we are used to seeing in lab recorded experiments. For instance, motion artefacts related to walking, moving the head to explore an environment, or climbing stairs, will be larger outside of the lab. Additionally, we can expect substantial physiological changes that can corrupt the brain measures, particularly in the case of fNIRS (see recent review in [9]). To counter this, wearable neuroimaging devices should be designed to minimize sensor displacement due to movement, and allow the simultaneous and synchronized recording of systemic physiology. Multimodal sensing of whole-body movement and physiology can also be used to offset motion artefacts in the data. Heart rate, respiration, eye-gaze, and body movement can all be used to provide context for better interpretation of the brain data – and can provide a way of automatically segmenting brain data for block-like experiments [4]. Beyond improving signal quality, being able to simultaneously study brain and behaviour is crucial to fully understand brain functioning as the brain is not an isolated organ, but is embodied, and communicates with the outside through the body.

In addition to sensing, new algorithms are also needed to ensure good signal quality and robustness to interference. Machine learning and classification algorithms are a hot topic at the moment in the neuroimaging field, with the premises of improving the discrimination of the brain activation patterns between different populations (e.g., neuroatypical vs typically developed) or different cognitive states (e.g., rest vs activation). However, the discrimination ability of existing algorithms is far from ideal. There is a clear need for new signal processing techniques and new statistical methods that can extract meaningful features and to assess significant changes in brain activity.

Finally, a major goal of brain sensing, particularly for applied or BCI systems, is to be able to interpret and act on a single reading, without repetition, in real-time. That is, we need 'one-shot' detection without requiring, for example, a person to persistently repeat imagining a movement 10 times, with rests in-between, as is the case for current systems. Existing BCIs require a lot of user training, and are not robust to long-term use. Combining modalities, like EEG and fNIRS, has the potential to improve this situation, as does the use of new pattern recognition algorithms [7].

CONCLUSIONS

The opportunities offered by wearable brain sensing are extensive. In many ways neuroscientists will have to start from the basics, expand on what has been learnt about the brain from traditional testing, and build on this to uncover new knowledge about the inner functioning of the brain in novel situations that could not previously be recreated in the lab. Engineers and computer scientists are needed to support this work by developing new sensing hardware and algorithms. In the push towards greater ecological validity in brain sensing, expertise in wearables – on multisensory fusion, low-power design, context recognition, and unobtrusive wearability – will be essential. Advances in wearable brain and body sensing are already starting to push the boundaries of neuroscience forward, but it is important to acknowledge the limitations of what is and what is not possible. Outside a repeated block design, it is currently difficult to make meaningful inferences from real-time brain signals. So, given current technology, applications that are built on the premise of reading and interpreting cognitive processes may not always work as well as might be hoped. However, with continued advances both in sensing and neuroscientific research, wearable applications using real-time brain sensing may one day become commonplace.

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REFERENCES

[1] E. Boto, Holmes, N., Leggett, J., Roberts, G., Shah, V., Meyer, S. S., & Barnes, G. R., “Moving magnetoencephalography towards real-world applications with a wearable system,” *Nature,* vol. 555, no. 7698, 2018.

[2] R. Coben, M. Linden, and T. E. Myers, “Neurofeedback for Autistic Spectrum Disorder: A Review of the Literature,” *Applied Psychophysiology and Biofeedback,* vol. 35, no. 1, pp. 83, October 24, 2009.

[3] F. Dehais, A. Duprès, G. Di Flumeri, K. J. Verdière, G. Borghini, F. Babiloni, and R. N. Roy, "Monitoring pilot's cognitive fatigue with engagement features in simulated and actual flight conditions using an hybrid fNIRS-EEG passive BCI," *IEEE SMC*, 2018.

[4] A. Hamilton, P. Pinti, D. Paoletti, and J. A. Ward, "Seeing into the brain of an actor with mocap and fNIRS," *Proceedings of International Symposium on Wearable Computers (ISWC).* pp. 216-217.

[5] S. A. Huettel, Song, A. W., & McCarthy, G., *Functional magnetic resonance imaging*, Sunderland, MA, 2004.

[6] C. T. Lin, Ko, L. W., Chang, M. H., Duann, J. R., Chen, J. Y., Su, T. P., & Jung, T. P., "Review of wireless and wearable electroencephalogram systems and brain-computer interfaces," *Gerontology,* vol. 56, no. 1, pp. 112-119, 2010.

[7] N. Naseer, and K.-S. Hong, "fNIRS-based brain-computer interfaces: a review," *Frontiers in Human Neuroscience,* vol. 9, no. 3, 2015-January-28, 2015.

[8] G. Pfurtscheller, & Da Silva, F. L. , " Event-related EEG/MEG synchronization and desynchronization: basic principles.," *Clinical neurophysiology,* vol. 110, no. 11, pp. 1842-1857., 1999.

[9] P. Pinti, Aichelburg, C., Gilbert, S., Hamilton, A., Hirsch, J., Burgess, P., & Tachtsidis, I. , "A Review on the Use of Wearable Functional Near-Infrared Spectroscopy in Naturalistic Environments," *Japanese Psychological Research,* vol. 60, no. 4, pp. 347-373, 2018.

[10] F. Scholkmann, Kleiser, S., Metz, A. J., Zimmermann, R., Pavia, J. M., Wolf, U., & Wolf, M. , " A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology," *Neuroimage*, no. 85, pp. 6-27, 2014.