Expanding EEG research into the clinic and classroom with consumer EEG systems

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Abstract

Recent advances in electronics and computing technology have made the development of new forms of EEG measurement possible. There are now systems that are: significantly lower cost than traditional systems (on the order of 1,000 USD); based on saline and dry electrodes allowing simple setup and recording; and producing sufficiently good quality signals for use in some research contexts. Here we briefly review the research use of one of the most popular of these new systems: the Emotiv Inc. EPOC/EPOC+ "Contextual EEG System." We also present specifications of a representative sampling of other systems that are also lower cost compared to traditional EEG and share our experiences using the Emotiv EPOC in several ongoing studies in our laboratory. We conclude that while the earlier systems like the Emotiv may have challenges for use in research, these consumer-grade EEG systems represent a useful addition to certain types of EEG research.

Introduction

Electroencephalography (EEG) is firmly established as a research tool throughout experimental psychology and cognitive science; however, its clinical use has historically been primarily limited to medical evaluation. Over the past 15 years, the costs of the underlying electronics required to build EEG hardware has decreased by a factor of 100, creating the incentive for new manufacturers to enter this market with low-cost "consumer grade" hardware. While some of this equipment is not powerful enough for use as anything more than a toy or entertainment device, there are now several EEG systems that are sufficiently sophisticated for use both in some clinical research applications and in educational settings, while being priced below 1,500 USD. Additionally, there are new systems in the 10,000 USD range that claim to offer performance equivalent to systems costing 2 to 10 times as much. Here we focus on systems at the lower price point (see Table 1 for examples).

In addition to the dramatic reduction in the cost of these EEG systems, they make use of the many modern advances in EEG electrode design. These systems offer a variety of electrode configurations: ranging from dry electrodes which require no significant preparation and saline electrodes that require only a small amount of liquid applied to the scalp, to gel and paste electrodes sets that are comparable with more traditional EEG systems used in laboratory research. In addition to the increase in participant comfort, these newer electrode technologies allow for fast setup, with well-practiced experimenters being able to set up the headsets for recordings in under 5 minutes.

Other benefits of these systems are that they interface with commodity PCs, Macs, and smartphones directly through standard interfaces and work in rooms that are not specially shielded for EEG. This combination of features allows for a level of portability that is previously unheard of in EEG data collection. Finally, several of the newest systems allow for wireless connections between the EEG collection headsets and the host computer recording the data providing excellent ease of use in complex environments.

With these and other advantages, the opportunities for moving EEG out of specialized, purpose-built laboratories and into more naturalistic settings are many. Within reasonable limits, some amount of EEG can now be collected almost anywhere. These systems can be used for a wide variety of research purposes, such as EEG neurofeedback, EEG spectral and time-frequency analyses, and so on. Most of these systems do not readily allow the collection of event-related potentials (ERP), although there are effective hardware modifications available in the published literature to allow very precise ERP measurement, as well as software tools that allow less accurate, but acceptable quality ERPs (Badcock et al., 2015; Ekanayake, 2014).

The main limitation of these systems is that they are low-density, ranging from one or two electrodes up to 16 or 32 for some of the more expensive mid-tier systems. Here we exclusively discuss EEG systems that are multi-electrode (with a minimum of 8 sensors) and that either have previously been used in some form of research or show a strong potential for such use.

Review of Research Using the Emotiv EPOC/EPOC+

The first of these new systems to provide sufficient signal quality for research use was the Emotiv EPOC system. This was later replaced with the upgraded EPOC+ system. Both systems provide 14 channels of EEG (see Table 1 for details), a 128 Hz sampling rate (in terms of data returned to the researcher), and multi-axis gyroscope.[1] As the Emotiv EPOC was the first of these systems available, it has the most extensive research literature, although much of this literature is comprised of conference papers rather than peer-reviewed research. In this section, we briefly review this literature to provide some sense of the range of studies that have been conducted with this of equipment.

Brain Computer Interfaces (BCIs). The Emotiv EPOC has been used as a component in numerous studies of Brain Computer interface and Human-Machine interface research. Its gyroscope and ability to discern facial gestures (via Emotiv's Expressiv software, recently renamed "Facial Expressions") has been used to help those with physical disabilities to connect with those around them (Krishnaswamy & Kuber, 2012). The facial movements has been used in BCI work to simulate a button press in a smart home (Lee, Nisar, Malik, & Yeap, 2013), simulate a button press in a P300 speller (Al Mamun, 2014), and to create a hands-free Geospatial information system via (Carter, 2012). It has also been used to control a wheelchair with head gestures (Rechy-Ramirez, Hu, & McDonald-Maier, 2012). Raw EEG analysis with the EPOC has been used to create motor imagery BCI systems (Martinez-Leon, Cano-Izquierdo, & Ibarrola, 2016) and for rehabilitation via Motor imagery in a video game (Muñoz, Ríos, & Henao, 2014).

Emotion analysis. Emotiv provides a software package formerly called the "Affective Suite" (now renamed "Performance Metrics") which provides to the researcher signals related to emotion that are derived from the EEG. We note, however, that this software is closed-source and its algorithms are not published openly, so the meaning and definition of the signals is not completely known to the research community. Despite this, the software has been used by researchers (especially in Human Computer Interaction and User Experience research projects) to determine emotional states in research participants. The software reports the following measures: Engagement/Boredom, Frustration, Meditation, Instantaneous Excitement, and Long-Term Excitement.[2] For instance, it has been integrated with a system to help video games adapt to users' emotions (Bernays et al., 2012), used to help identify emotions during a tutoring session (Harrison, 2013), and used to measure cognitive load in a learning environment with logic puzzles (Joseph, 2013).

[1] The EPOC+ offers a 256 Hz sampling rate mode, but this is apparently only available to users via the web-based "PureEEG" application which is not compatible with our human subjects research requirements, so we are unable to test this option.

[2] See the Emotiv website for more details: https://emotiv.zendesk.com/hc/en-us/articles/201216195-Five-Basic-Measures-of-Mental-Performance-Metrics but note that the specific signal processing steps that turn raw EEG into these derived signals is proprietary and not revealed by the company.

EEG spectral analyses. Spectral analyses using the EPOC are relatively common. It has been used to assess participant preference for a product, for marketing purposes (Khushaba et al., 2013); to measure the impact of perceived quality on emotional video experience (Antons, Arndt, De Moor, & Zander, 2015); and to create an interactive museum experience(Abdelrahman, Hassib, Marquez, Funk, & Schmidt, 2015). Investigators have also used it to develop security systems based on brainwaves (Klonovs, Petersen, Olesen, & Hammershøj, 2012) and attempted its use as a mind reading device (Adelson & Schapire, 2011).

Event Related Potentials (ERP). The Emotiv EPOC was not designed with ERP collection in mind. It has no hardware input for signals that allow recordings to be locked to a stimulus. Despite this, it has been modified to collect ERP data with some simple hardware changes (de Lissa, Sörensen, Badcock, Thie, & McArthur, 2015), and with clever software workarounds (Ekanayake, 2014). This has allowed the recording of ERPs in children (Badcock et al., 2015; de Lissa et al., 2015) and several experiments using a P300 paradigm (Campbell et al., 2010; Duvinage et al., 2012). The EPOC has also been used to help filter noise in hearing aids (Hanson & Odame, 2015), for monitoring language processing by source localization (Louwerse & Hutchinson, 2012), to recognize mental workload (Putze & Schultz, 2014) and to build an interface to control mobile phones via brain wave regulation (Campbell et al., 2010), all with the P300 paradigm.

Comparisons with traditional EEG systems. There are publications explicitly comparing the Emotiv EPOC's performance to standard laboratory EEG. One of the initial concerns by the research community was determining if the Emotiv EPOC was detecting true EEG signals or just detecting muscle noise. This has been addressed in a widely read white paper and its several follow-on revisions (Ekanayake, 2014). That said, as a consumer grade system, it is not as reliable (in terms of signal variability) as laboratory grade equipment. Despite this, and because of quick set-up and its easy portability, Badcock and colleagues deem it "a promising tool for measuring auditory processing" using the ERP paradigm (Badcock et al., 2013). They also note that the devices portability allow collection in many places outside of the laboratory: schools, child-care centers, hospitals, and private clinical practices (Badcock et al., 2015).

Review of Systems: Hardware

These systems are undergoing constant change, with new equipment coming on to the market regularly. However, as of late 2016, Table 1 provides an overview of available equipment in this category. The prices for each system vary by the specifics of the configuration but is usually around $5,000, with more capabilities in the more expensive systems at $12,000 and up. The main differences among the systems are the number of channels provided, electrode type, and headset or cap type. There are also differences in engineering, design, and software. We summarize them in Table 1 and review a selection in the following section.

Table 1

Summary of Consumer-grade EEG systems available in late 2016

Manufacturer	Emotiv[a]	OpenBCI	OpenBCI[b]	OpenBCI	Wearable Sensing[c]	Brain Rhythm Inc.[d]	Brain Rhythm Inc.	Brain Products[e]
System Name	EPOC (+)	Mark IV	Nova	Supernova	DSI-24	BR32S	BR8 Plus	actiCAP Xpress
Number of Electrodes	14	8/16	8	16	24	32	8	32
Electrode Type	Saline electrodes	Wet, dry, or active	Wet, dry, or active	Wet, dry, or active	Foam or Spring-loaded	Foam or Spring-loaded	Dry	Passive, passive actively, true active
Flexible locations	No	Yes	Yes	Yes	No	No	No	Yes
Flexible Reference	No (Mastoid/P3)	Yes	Yes	Yes	No	Yes	No (Earlobe)	Yes
Price	$799	$2000	$1000	$1700	$20,000	~$12,000	~$4500	$6991+
Sampling Rate Internal	2500	250 SPS/125 SPS	250 SPS	125 SPS	300 Hz	250Hz	1000Hz	100kHz
Access to Raw Data	no	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Output File Type	EDF	CSV	CSV	CSV	CSV & EDF	EDF	CSV & EDF	EEG

[a] https://www.emotiv.com/ [b] http://openbci.com/ [c] http://www.wearablesensing.com/
[d] http://www.bri.com.tw/about.html [e] http://www.brainproducts.com/

Emotiv

The EMOTIV EPOC/EPOC+ offers a headset with 14 electrodes plus a reference, a single set of electrode felts, and a USB receiver for recording data on a PC. All the equipment is assembled for the user, and it is ready to go out of the box. One of the best features of the Emotiv system is the ability to get EEG recording started within a very short time of receiving the equipment; most people can get it working the first day or so and will be sufficiently familiar with the equipment to be using it within a few days.

The original EPOC was available with a program called "test bench" for collecting raw EEG and researchers could also obtain a software development kit (SDK) for developing new programs that access raw EEG. This latter has been discontinued by the company, although a much more limited open source SDK (called the "community SDK") is available online at Github (https://github.com/Emotiv). While some of the code is open source, this community SDK does depend on critical proprietary software components. Also, the currently available SDK does not allow access to raw EEG signals, only to derived quantities, such as averages of band powers, etc. As of the latter half of 2016, access to the raw EEG signals is only available with a monthly subscription to the company's "Pure EEG" software, which unfortunately limits the number of raw EEG recordings available per month (see: https://www.emotiv.com/product/emotiv-pure-eeg/).

The electrodes provided are at international 10-20 locations: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4. There is a fixed reference electrode at P3 (Emotiv labels this the CMS or "common mode sense") and a "driven right leg" (DRL) at P4. The CMS is the actual electrical reference for the EEG recordings, the DRL provides a feedback noise cancellation system and is not a reference in the EEG sense. (This point is sometimes confused, particularly in internet discussions of the equipment.) In principle, it is possible to re-wire the reference electrode site to a different configuration, and there are reports on the internet of people doing so, but this voids the manufacturer's warranty.

The Emotiv EPOC/EPOC+ uses saline felt electrodes. The electrodes are gold-plated disks, and a round felt, wetted with saline, is placed in between this disk and the scalp. The headset is springy and will press the wet felt into the scalp firmly (though not uncomfortably) to provide a good electrical connection.

As noted above the system provides data to the user at an effective sampling rate of 128 Hz, although per the technical specifications it works at a rate of 1024 Hz internally. The down sampling is for various technical reasons including wireless transmission to the receiver. Resolution is approximately 0.5 microvolts (14 bits). The working bandwidth is 0.2 to 43 Hz, allowing recordings into the low gamma range, and there are notch filters at 50 and 60 Hz for electrical noise in both North America and Europe. Most of these details can be found on the manufacturer website.[3]

OpenBCI

OpenBCI is a start-up company that began as a kickstarter campaign to make EEG hardware specifically for amateur scientists. Their system prices vary most dramatically because they offer completely disassembled, partially assembled, and professionally assembled versions of each model. Researchers should note that the OpenBCI family of systems will require more hands-on attention and tinkering than the other options. The benefits of this are more direct access to the system's features the cost is needing to know more about electronics or a willingness to use the many online discussion forums dedicated to these systems. As this is a system we are currently working with, we believe that the technical skills needed are not excessive and fall well within the range of a motivated researcher.

Their systems require the purchase of a headset (literally an empty electrode holder made from 3D printed plastic) and an EEG acquisition system that provides 8 or 16 channels. The acquisition system is based on the Texas Instruments ADS-1299 analog-to-digital converter which is built specifically for EEG and ECG (electrocardiogram) applications. This EEG acquisition system may also be used with traditional EEG caps and electrodes in lieu of a headset.

An important feature of the OpenBCI system that deserves special mention is that it is based on open-source hardware architecture; the designs for the system are available to any researcher that wants to download them. It is relatively easy to modify the designs for special applications. Additionally, the entire system has been built from the ground up to work with open-source EEG software packages. This makes the entry price for researchers new to EEG relatively low, and it also provides some "future-proofing" in that the company cannot change their policies to lock users out; if they do, the readily available designs allow continued using the equipment unimpeded.

The OpenBCI is flexible about electrode location. With a standard 32 channel electrode cap, it can record simultaneously from up to 16 electrodes. There is an additional reference channel (called SRB) that may be used to provide a common reference to all the other electrodes, or the electrodes can be referenced to each other in a variety of ways. This allows a much greater flexibility in reference location. Additionally, several of the kits from OpenBCI support the use of ear clips for earlobe referencing, which is impossible with the Emotiv system in its default configuration. The OpenBCI acquisition module provides a "bias" channel that can be used to provide similar functionality to the DRL of the Emotiv. Additionally, the flexibility in references may be extended by rewiring the reference location to dual electrodes or ear clips to provide a bilateral reference. Given the design of the OpenBCI system, this is easier and less risky than

[3] See: https://www.emotiv.com/product/emotiv-epoc-14-channel-mobile-eeg/.

for the Emotiv EPOC. However, the OpenBCI's warranty is much more limited than the Emotiv's given the "open" nature of the system.

Electrodes for the OpenBCI can be dry, spring-loaded dry, or conductive paste. The spring loaded dry electrodes are especially useful for quick setup; these electrodes gently push through the hair onto the scalp for good contact, with "fingers" that go between hairs as they press down. In contrast to some other fixed systems, the OpenBCI system can be adapted for use with any electrodes that might be available to the researcher, given the open design and architecture.

Using the headset designs from OpenBCI, the Ultracortex Mark IV for instance, up to 35 of the electrode locations in the international 10-20 system may be targeted (although only 16 of them may be recorded from simultaneously). Please see the OpenBCI website for more details on electrode locations.

The OpenBCI system allows more direct access to the electronic hardware and therefore its specifications are harder to describe. The Texas Instruments ADC has sampling rates from 250 Hz to 16 kHz, but most configurations of the OpenBCI equipment work at 250 Hz (twice the speed of the EPOC and roughly equivalent to the EPOC+ in its high-speed mode). Resolution is 0.02235 microvolts (24 bits). There is no specific filtering for electrical line noise at 60 Hz, but a common-mode rejection circuit for the differential amplifier rejects some of this and can be combined with software filtering.[4]

Brain Rhythm

Brain Rhythm Inc. is a relatively new company in EEG, offering 8 and 32 channel wireless EEG systems. These systems can use spring-loaded dry electrodes (like the OpenBCI system) or an innovative foam-block type dry electrode. Their 32-channel system (the BR32S) uses an electrode cap similar to traditional research EEG systems, while their 8-channel system (the BR8+) uses a design similar to the Emotiv EPOC, although with a very different shape. The Brain Rhythm systems are not open hardware architecture, but the company does support the major open-source EEG analysis software systems.

The sampling rate is 250 Hz for the BR32S and 1000 Hz for the BR8+; the latter being dramatically better than other systems discussed here, although it is worth noting that EEG signals of interest lie below 50 Hz for the most part and therefore may be adequately sampled at rates of > 100 Hz (due to the Shannon sampling theorem in signal processing). However, faster sampling rates do provide some improvements in signal quality and precision. Resolution is 16 bit (BR32S) or 24 bit (BR8+) and so comparable with the previous systems. Unlike the Emotiv there is a hardware input for event/stimulus locking allowing ERP collection without having to modify the hardware.

[4] See: http://openbci.com/forum/index.php?p=/discussion/136/50hz-power-filter-rather-than-60hz-power-filter for a discussion by one of the developers on this point.

The BR8+ has electrodes at locations: FP1, FP2, FZ, C3, C4, PZ, O1, and O2. The BR32S covers most of the locations in the 10-20 system's standard 32 electrode configuration; plus AF3 and AF4. The 32 channel BR32S is the only one of these lower cost systems that provides a level of coverage comparable with more expensive medical or research systems.

The electrode designs are the most unusual of the systems reviewed. The foam block electrodes can be compressed in the electrode cap to squeeze against the head and provide significant surface area for the electrical connection. The spring-loaded electrodes are also a dry electrode design, and have a similar design to the OpenBCI system; they have pins that can press in between hair and make good contact with the scalp.

Data Types and Access

All the systems allow access to the raw EEG data for the researcher, in some form or another. For OpenBCI and Brain Rhythm, the data is available directly; Emotiv recently changed access to require their web-based data analysis app.[5] The data is provided in EDF (European Data Format) and CSV (comma separated value), both of which are well-supported in EEG analysis software. Conversion tools for these formats are available on the internet.

ERP Possibilities

Both the OpenBCI and the Brain Rhythm systems allow hardware level timing signals to be recorded along with the EEG. The Emotiv system cannot directly record ERPs but the system has been modified to do so (Badcock et al., 2015; de Lissa et al., 2015; Ekanayake, 2014).

<u>Review of Systems: Software</u>

Traditional research EEG systems have historically come with their own, tightly integrated, proprietary software made by the equipment manufacturer (see for example Electric Geodesics Inc. and their software Net Station[6]). These software packages tend to provide a "pick list" of standard analysis methods. There may be more advanced features that allow various data plots and simple analysis. Investigators have had to choose between simple packages allowing standard analyses or working with software that demands more computational skill from users. Most research-grade systems allow the exporting of EEG data in standard formats; the systems reviewed here allow this, too, with some restrictions for Emotiv as already noted.

A variety of open-source/freely available software packages are available online. Many of these packages require the commercial software system MATLAB (The Mathworks, Inc.) to run. While MATLAB is commercial and therefore not free, it is well supported at many colleges and

[5] See: https://www.emotiv.com/epoc/ (accessed on 1/29/2017).
[6] See: https://www.egi.com/research-division/geodesic-eeg-system-components/eeg-software.

universities which maintain site licenses allowing users on campus to run MATLAB without additional cost.

EEGLAB and Related Systems

The most important of the MATLAB based systems is EEGLAB.[7] This software is well-known and used widely in the research community, and can be viewed as a *de facto* standard against which analyses may be compared. It offers a graphical user interface (GUI), data visualization, and several standard analyses built-in, as well as being fully extensible for researchers wanting to implement new analyses. With the GUI, many analyses may be completed with the simple press of a button because good default values for parameters are usually provided. This is especially good for people starting out in EEG research. As the understanding of EEG broadens, the system has many options for which one can change the analytic pipeline. It has a long development history with mailing lists and other user support for getting started (Delorme & Makeig, 2004).

There are several software systems designed to be plugged into EEGLAB. ERPLab is an open-source MATLAB package for analyzing ERP data.[8] It provides tools for preprocessing EEG data for ERP studies, and for analyzing and evaluating the results. It has additional features more generally useful, for instance, it can automatically detect and mark eye blinks in the raw EEG data. FieldTrip is a toolbox for EEG source localization, something that is not relevant for small electrode arrays such as those reviewed here, but it adds numerous features to EEGLAB when installed.[9]

Python Based Systems

The Python computer language (Python Software Foundation[10]) has become one of the leading scientific programming languages over the last decade and a half. This is because of its clear and easy to read syntax, well-supported software libraries, and broad support of mathematical, statistical, and other core scientific programming requirements.

Because of these general features, Python has become important in neuroimaging (functional magnetic resonance imaging, or FMRI) and cognitive neuroscience (EEG, and also Magnetoencephalography, or MEG). The MEG and EEG analysis and visualization system (MNE) is a powerful Python-based packaged for EEG and MEG processing, analysis, and machine-learning approaches (Gramfort, 2013).[11] MNE has similar preprocessing possibilities to EEGlab. It has the ability to work with Freesurfer (Dale, Fischl, & Sereno, 1999) and is good for

[7] Downloadable from: https://sccn.ucsd.edu/eeglab/.
[8] Downloadable from: http://www.erpinfo.org/erplab.html.
[9] Downloadable from: http://www.fieldtriptoolbox.org/.
[10] More information is available from: https://www.python.org/psf/.
[11] http://www.martinos.org/mne/stable/index.html.

MEG data as well as EEG data. They have a helpful forum to help migrate from EEGlab to MNE.

R Based Systems

The R statistical language is in wide use in scientific data processing and analysis, it is the *de facto* international statistical programming language. It supports a variety of mathematical operations, for instance, it can perform any of the analyses that MATLAB can do, albeit in different notations, and it implements the cutting-edge methods of statistics and signal processing. Although not as heavily developed as the systems for MATLAB and Python, R has several add-on packages for EEG, such as eegkit, for more complex non-linear EEG analyses (R Core Team, 2013).[12]

Research Use Examples

As examples of the research use of the EPOC system, we discuss two ongoing projects in our lab. The first is a series of studies to determine the viability of using the EPOC to measure inter-hemispheric spectral power differences, specifically the frontal cortical alpha asymmetry which has a long history of research use (Coan & Allen, 2003a, 2004, 2003b). The second is an analysis of short- to long-time EEG recordings of mindfulness meditation practice and the development of measures of performance change as the participants develop in the practice. These studies are particularly suitable for the EPOC system as they are based on spectral power estimates from just a few regions, rather than requiring higher density electrode arrays.

Frontal Cortical Alpha Asymmetry (FCA)

It is well established that there is a subject-specific asymmetry in activation across the frontal cortex in the alpha band of the EEG spectrum. This frontal cortical alpha asymmetry (FCA) is both trait (differences in resting FCA measurement) and state related. As a trait difference it is related to depression (Allen & Reznik, 2015; Allen, Urry, Hitt, & Coan, 2004; Davidson, 1998; Jesulola, Sharpley, Bitsika, Agnew, & Wilson, 2015; Vuga et al., 2006), anger (Allen, 1998), stress (Quaedflieg, Meyer, Smulders, & Smeets, 2015), and post-traumatic stress disorder (Meyer et al., 2015) among others. Various manipulations have shown that the short-term value of the FCA can be manipulated by activities such as squeezing a ball (Beckmann, Gröpel, & Ehrlenspiel, 2013; Cross-Villasana, Gröpel, Doppelmayr, & Beckmann, 2015; Harmon-Jones, 2006) and may also be influenced by time of day or season (Peterson & Harmon-Jones, 2009). The FCA measure is connected to many differences of clinical interest making it a useful adjunct for many studies.

The FCA measure can be defined in various ways. It is basically a comparison between power in the alpha band (8-13 Hz) on the left side compared with the corresponding power on the right

[12] https://cran.r-project.org/web/packages/eegkit/eegkit.pdf.

side. Note that alpha power is inversely related to cortical activity, so greater alpha power on the left, say, would indicate lower cortical activity on that side. We use the measure defined by Coan and Allen(Coan & Allen, 2004), which is the logarithm of average alpha power on the left side minus the right, which is equivalent to the log of the ratio of the powers:

$$\log(\text{right alpha power}) - \log(\text{left alpha power}) = \log\left(\frac{\text{right alpha power}}{\text{left alpha power}}\right)$$

Our primary goal in this initial work is to show that the FCA may be reliably collected using low-cost EEG hardware. We proceeded in two steps: first, we showed that the resting FCA displayed sufficient individual variation. Second, we replicated a study using hand squeezing (pumping) and demonstrated that the direction of average changes in the FCA was like that seen in previous work.

One of the challenges with the Emotiv headset is that it has a single fixed reference electrode position; either the left mastoid (the bony protuberance behind the ear) or at the P3 electrode location. When recording EEG, the electrical voltages are only defined relative to a reference; that is, voltages are intrinsically differences. Generally, locations with less neural activity are preferred, so most research users choose the left mastoid. The problem with the left mastoid is that this location is lateralized, and for the FCA, which is itself a difference between sides of the head, this gives an undue weighting to the left (versus the right) signals used to compute the difference. In our first experiment, we found that the data were sufficiently clean enough, with no excessive pre-processing, to reveal important features of the EEG. In Figure 1 we show an example of 45 s of resting state EEG traces from one of the subjects in this study as an example of the data.

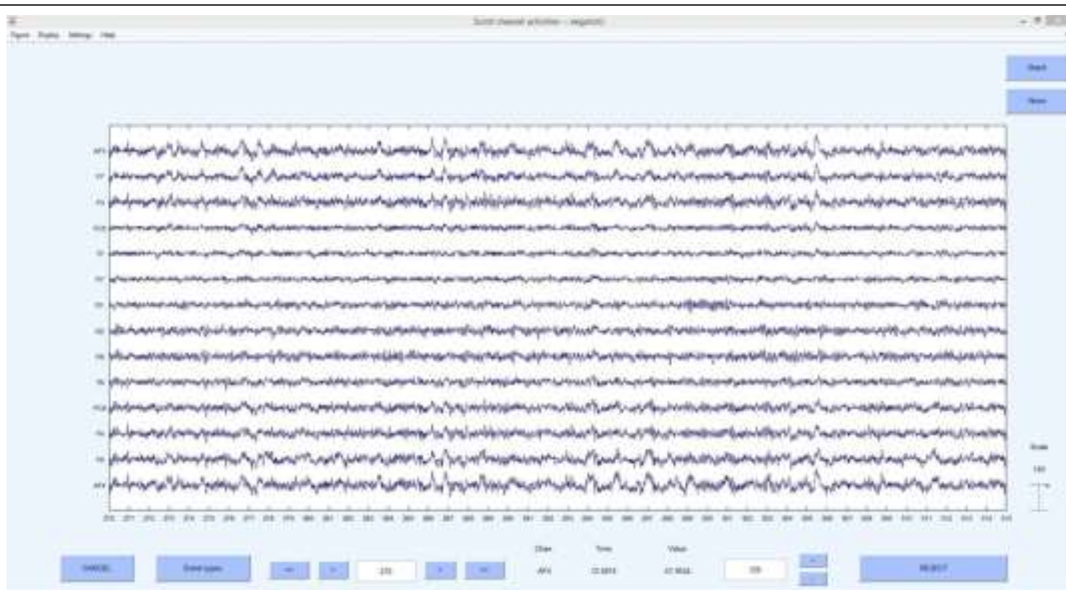

Figure 1. A typical EEG trace using the Data Scroll in EEGlab. It shows 45 seconds of resting data in the X axis, and the 14 electrode locations stacked along the Y axis.

We found individual subjects with both left and right oriented resting relative FCA measures. This confirmed that individual differences were strong enough to exceed any limitations due to the one-sided EEG reference. We also examined the differences between the alpha asymmetry score with the eyes open and eyes closed, as shown in Figure 2. While different electrode pairs (F3 & F4, or FC5 & FC6) show different overall levels of FCA, the individual subjects' FCA is not strongly affected by being measured with eyes open or eyes closed.

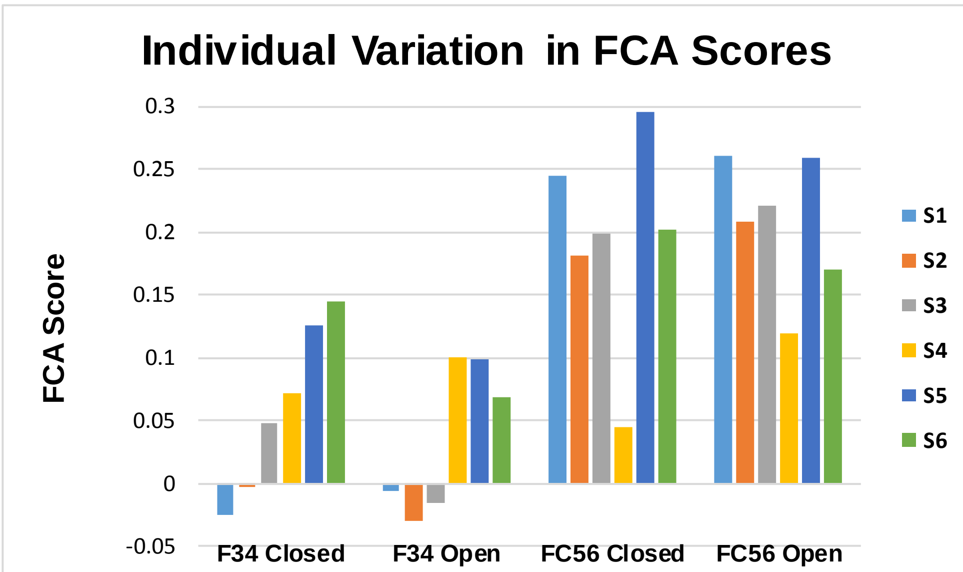

Figure 2. This figure shows individual variation of subject's EEG using the Emotiv EPOC. Each bar of a color is a single subject. The extended electrodes sites of the 10/20 system used were F3, F4, FC5, and FC6. The FCA score is calculated by the right minus the left. This produces alpha asymmetry scores as F34 (F4-F3) and FC56 (FC6-FC5). The FCA for eyes open and eyes closed is similar within subject and electrode site.

In our second experiment, we demonstrated that the high alpha (10-13 Hz) FCA can be manipulated by a hand-squeezing task. We collected data on 6 subjects with 8 sessions each and looked at the left-hand data only. There was no effect on the right-handed data, consistent with (Harmon-Jones, 2006). Each participant was taken through a 2-minute period of resting baseline, 1 minute of hand contraction (squeezing a rubber ball with approximately 1 Hz pulses), and a second 2-minute period of rest. The comparison was between the pre- and post-FCA measured from the FC5 and FC6 electrode sites. We detected this change using a difference score derived from the global-power-adjusted metric of alpha power (Smith, Zambrano-Vazquez, & Allen, 2016). We note that the effect was strong at the FC sites ($t(5) = 3.74$, $p = 0.013$), but not significant in the comparison between the F3 and F4 sites. Additionally, other measures of asymmetry did not produce statistically significant results. We continue the work on this to determine if we can derive a reliable and more robust measure of FCA that can be obtained with the EPOC system.

Tracking Changes in Mindfulness Meditation

We have been conducting studies of mindfulness meditation training for anxiety reduction.[13] These studies consist of 8-week small-group sessions where the participants talk about their experiences with meditating, do a guided group meditation, and learn mindfulness techniques to deal with anxiety. Each week the length of the meditation increased, starting at 7 minutes increasing to 45 minutes. Between sessions, participants are asked to practice meditation at home. The goal with the EEG component of the research is two-fold: first, to identify early markers of EEG activity that correlate with later success in the intervention; second, to identify markers in the EEG that relate to ongoing participant performance in meditation.

Based on previous research, we decided to focus on measures derived from spectral representations of the EEG signals (Banquet, 1973; Cahn & Polich, 2006; Lagopoulos et al., 2009). These measures depend primarily on moving averages of the power in each frequency range of the EEG signal's spectrum. Frontal theta is associated with concentration, which may reflect increased awareness (Aftanas & Golocheikine, 2001). It has been shown that alpha and theta powers are increased in meditation practice as compared to rest. This is the difference between the overall power in the alpha band (8-13 Hz) and the theta band (4-8 Hz) compared as a ratio. This change can be used as a marker of successful meditation practice. These analyses are ongoing to help determine if meditation can help identify physiological markers of reduction in anxiety.

Conclusions

The consumer grade EEG systems are becoming more common, with many options available to the researcher. There are limitations in each system's capabilities, and carefully matching the research program to the equipment may be necessary to avoid investing in equipment which can't be used to address a specific question. These systems are best used for robust measurements such as alpha, or other spectral comparisons, or for the study of slow changes over longer EEG time-course recordings. However, these systems have high portability to the clinic or other settings, and they have an ease of use which is still an advantage. Careful choice of research measures, paired with this type of equipment, allow researchers to add a psychophysical component to many research programs that currently do not have such a component but would benefit from one.

[13] This research is being conducted with Dr. Aki Masuda, Matthew Donati, and Ward Schaefer. Dr. Masuda is currently at the University of Hawaii.

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