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ARTICLE
Neurogaming Technology Meets Neuroscience Education: A Cost-Effective, Scalable, and Highly Portable Undergraduate Teaching Laboratory for Neuroscience

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Active research-driven approaches that successfully incorporate new technology are known to catalyze student learning. Yet achieving these objectives in neuroscience education is especially challenging due to the prohibitive costs and technical demands of research-grade equipment. Here we describe a method that circumvents these factors by leveraging consumer EEG-based neurogaming technology to create an affordable, scalable, and highly portable teaching laboratory for undergraduate courses in neuroscience. This laboratory is designed to give students hands-on research experience, consolidate their understanding of key neuroscience concepts, and provide a unique real-time window into the working brain. Survey results demonstrate that students found the lab sessions engaging. Students also reported the labs enhanced their knowledge about EEG, their course material, and neuroscience research in general.

Key words: electroencephalography (EEG); event-related potential (ERP); cognitive neuroscience; enquiry-based learning; research-enhanced learning.

The current consensus among education researchers is that undergraduate students learn academic subject matter including science better when active, enquiry-based approaches are employed (Kahn and O'Rourke 2004; McNeal and D'Avanzo, 1997). Similar conclusions have been reached about undergraduate neuroscience education (Ramirez, 1997), especially highlighting the importance of student research experiences (Boitano and Seyal, 2001; Brew 2006; Zimbardi and Myatt, 2014). The benefits of integrating technology into neuroscience curriculum have also been reported (Griffin, 2003). However, relatively few introductory neuroscience courses offer students genuine opportunities to participate in hand-on research activities or obtain meaningful laboratory experience (for prominent exceptions, see Hurd and Vincent, 2006; Nyhus and Curtis, 2016). A primary reason for this deficit is that traditional laboratory-based activities typically require dedicated laboratory space and research-grade equipment, both of which can be prohibitively expensive in today's university environment (Steinmetz and Atapattu, 2010).

We report on an innovative project that aimed to integrate an active learning approach into an introductory undergraduate course in neuroscience within the major in Cognitive and Brain Sciences at Macquarie University (Sydney, Australia). The goal was to develop teaching labs that incorporated technology which was both cost-effective to implement and feasible for first-year undergraduates to learn to use over the course of a single semester. We decided on leveraging the latest in consumer neurogaming technology to create an affordable, scalable, and fully portable teaching laboratory that gives students invaluable opportunities to reinforce their understanding of fundamental concepts and methods in neuroscience by recording and visualizing their own brain activity in real-time. Specially, the laboratory used the EMOTIV Epoc+ (14 channel EEG) headset system (Figure 1; EMOTIV, San Francisco, USA) – a neurogaming headset recently established as a legitimate research tool in cognitive neuroscience research by two of the authors (Badcock and De Wit; Badcock et al., 2013, 2015 – to provide engaging brain imaging lab activities at a fraction of the cost of traditional neural recording systems.

Here, we demonstrate how the integration of the EMOTIV Epoc+ into an undergraduate curriculum can create exciting new opportunities for neuroscience education. We outline the hardware and software requirements for these teaching labs and discuss how they affected student learning experiences.

Figure 1. EMOTIV Epoc+ EEG system. *Left panel*: EMOTIV headset. *Right panel*: EMOTIV headset as worn by participant.

BACKGROUND

Electroencephalography (EEG) is a non-invasive brain-imaging method with excellent temporal resolution that occupies a central role in contemporary cognitive neuroscience (Senior et al., 2006; Luck, 2014). Frequently, researchers use EEG to investigate the neural responses (electrical potentials recorded from electrodes on the scalp) associated with specific sensory, motor, or cognitive events (e.g., a stimulus on a computer screen or a movement). By averaging neural activity across a large number of trials, the response to these events can be computed from the EEG signal, known as an event-related potential (ERP). Given the centrality of EEG, and more specifically ERP, in cognitive neuroscience research, introducing students to these techniques early in their studies is pedagogically valuable. However, incorporating EEG labs into neuroscience curricula has traditionally been an expensive venture, with research-grade systems costing between $50-100K (USD) per unit. Due to the additional need for dedicated lab space to house the fragile, bulky equipment, this price underestimates the true cost. On top of this, traditional EEG setups use a conductive gel to create low impedance connections between the electrodes and the scalp. Not only is this process messy (leaving gel in the hair that can only be properly removed by thorough washing), it is also lengthy (with set-up taking up to 30 minutes), which is undesirable for use in a classroom setting. As will be discussed shortly, EEG-based neurogaming systems do not exhibit any of these limitations.

One solution to these problems would be to have students focus on learning how to perform EEG data analysis without requiring them to collect data. Miller et al. (2008) adopt this approach and report on a “virtual EEG” software program involving “simulated” EEG data collection. However, a major limitation of this solution is that it prevents students from acquiring hands-on experience collecting real EEG data – a key aspect of the scientific research process.

Importantly, the emergence of relatively inexpensive and easy-to-use wireless EEG neurogaming systems stand poised to open up exciting new possibilities for neuroscience education (e.g., Schwarz et al., 2014). These systems for recording brain activity have been designed primarily to serve as supplementary controllers for software applications including games. Because they offer movement-free computer control, they have been playfully described as “joysticks” for the brain (O’Brien, 2014). Despite the original context for development, the relatively low cost of these neurogaming systems make them highly appealing as tools for undergraduate neuroscience education.

Many neurogaming systems are currently available, each with their own features and limitations. Some systems are relatively inexpensive but record data from a limited number of electrode channels, making them less useful for educational and experimental purposes. For example, the EMOTIV Insight ($299 USD, www.emotiv.com) and NeuroSky’s MindWave (from $99.99 USD, www.neurosky.com) are both low cost but provide only five channels of EEG data. By contrast, systems such as the EMOTIV Epoc+ ($799 USD, www.emotiv.com) are more expensive but offer 14 channels of EEG data. We used the EMOTIV Epoc+ (hereafter EMOTIV) because the wide distribution of the 14 electrode sensors offers considerable flexibility in terms of which brain areas can be recorded from. We also used the EMOTIV because it has recently been benchmarked against traditional research-grade EEG systems in terms of its design and usability (Hairston et al., 2014). It has also been shown that the EMOTIV is capable of recording research-quality neural data reflecting visual and auditory processing in both adults and children (Badcock et al., 2013, 2015; De Lissa et al., 2015; Yau et al., 2015).

The validation of EMOTIV as an effective research tool, together with its ease of use (low impedance connections between electrodes and the scalp are made with small cotton dental rolls soaked in saline solution – a process that leaves little to no residue and takes a maximum of 10 minutes to setup) make it possible to implement a fully functional, scalable, and cost-effective human brain-imaging lab in an undergraduate setting at a fraction of the cost of traditional EEG recording systems. Furthermore, due to the highly portable nature of the EMOTIV (and accompanying laptop computer), multiple units can be set up easily in most classroom environments, doing away with the need for costly dedicated lab space.

HARDWARE

The teaching labs employed EMOTIV Epoc+ systems (EMOTIV, San Francisco, USA), which were run on laptop computers (Macbook Pro, OS X El Capitan, 10.11.5, Intel Core i7, 2.7 GHz, 8GB RAM, and 1TB hard drive). The EMOTIV is powered by a built-in rechargeable battery and has flexible plastic arms fitted with gold-plated sensors aligned to the international 10-20 system (Jasper, 1958). The system is capable of recording EEG data from 14 channels (plus two reference channels) at a sampling rate of 128 Hz (or 256 Hz with updated firmware) with a single 16 bit analog-to-digital converter. This multiple-step conversion process takes place within the headset. Specifically, the original signal is filtered through a low and high-pass filter (cut-off frequencies of 83 and 0.2 Hz respectively) before the signal is digitized with a sampling rate of 2084 Hz. This digital signal is then filtered with a 5^{th}-order notch filter (50-60 Hz) before it is down sampled to 128 Hz (a sampling frequency that provides acceptable wireless transfer speed of the digital signal) and wirelessly transmitted to the USB receiver that is connected to the laptop. Although updated firmware enables the EMOTIV to down sample to 256 Hz, we elected to use the default setting of 128 Hz, as it was sufficient for instructional purposes.

To introduce students to the technique of ERP, the commercial EMOTIV system was modified with a custom-made event-marker system (Figure 2; Thie et al., 2012; Thie, 2013; also see Badcock et al., 2013 and De Lissa et al., 2015). This marker system allows real-time visualization of the temporal correlations between the events occurring during the experimental task and the recorded EEG signals. The system consists of an infrared transmitter unit and a receiver unit. The transmitter unit is connected to the audio output of the laptop and receives an audio signal every time a stimulus is presented. The unit then sends and amplifies and digitized infrared signal to the receiver unit attached to the side of the EMOTIV headset (Figure 2e). The output wires of the receiver unit are attached to two of EMOTIV’s sensors so that it can trigger an electrical pulse to mark stimulus onset in the recorded EEG data upon receipt of the infrared signal. This electrical pulse is visible at the time of data acquisition (in the data channels of the two sensors that the output wires are connected to), which allows students to observe the process of event-marking in real-time and solidify the concept of “timelocking” EEG activity to task events. It should be noted that other approaches including software-based approaches could be used. For example, real time data acquisition controlled by MATLAB code could embed digital triggers directly into the data (e.g., www.fieldtriptoolbox.org/development/realtime).

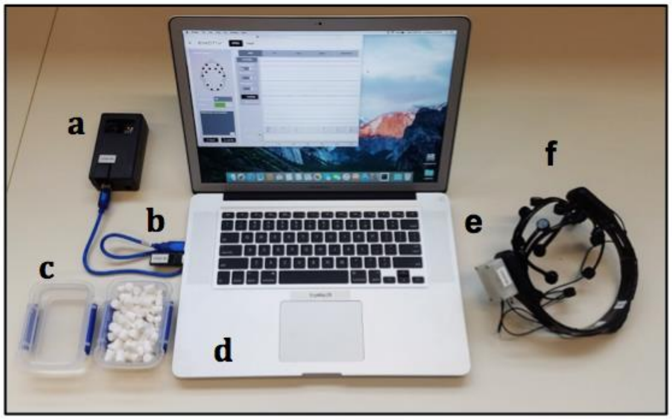

Figure 2. EMOTIV lab set-up. *Top panel*: Breakdown of lab items; (*a*) event-marker’s transmitter unit, (*b*) EMOTIV’s wireless USB receiver, (*c*) saline solution and cotton dental rolls, (*d*) laptop computer, (*e*) event-marker’s receiver unit, and (*f*) EMOTIV headset.

SOFTWARE

Two software packages were used during lab sessions: Emotiv Xavier TestBench (version 3.1.21) for visualizing and recording EEG, and MATLAB (version R2015b) for running the experimental task and processing of the EEG data. The TestBench software environment (Figure 3, top panel) provides three main interactive panels: (1) contact quality panel, (2) event log panel, and (3) EEG display panel. The contact quality panel visually represents the position of the sensors on the scalp and uses color variation to indicate sensor connectivity and quality of the EEG signal. Colors range from black through to green, with black indicating poor sensor connectivity (high impedance) and green indicating good connectivity (low impedance). The event log panel displays the connectivity of the wireless USB receiver and the pairing of the receiver with the EMOTIV headset. Finally, the EEG display panel provides a real-time visualization of the incoming EEG signals as well as artifacts such as eye blinks. The EEG display also registers electrical pulses triggered by the event-marker system (recall the recorded EEG signal and event-markers are saved in the same file for analysis). Although the focus in these labs was on the visualization and recording of the primary EEG signal using the EEG panel, TestBench can also display many other measures including a breakdown of the EEG signal into its component frequency domains (in the FFT panel) and the horizontal and vertical position of the head (in the Gyro panel). These features are also included in EMOTIV’s updated software package called PureEEG, which new customers are now required to download and use (www.emotiv.com/product/emotiv-pure-eeg).

MATLAB (R2015b) was used for running the experimental tasks and processing of the EEG data. The experimental tasks used in the Testing sessions were simplified versions of published experimental protocols (e.g., a face-recognition task used by De Lissa et al., 2015). This allowed students with limited experimental backgrounds to perform the experiment within the scheduled class times. For ease of use, and to prevent students from feeling overwhelmed when interacting directly with MATLAB code (the course presupposed no familiarity with MATLAB or any other programming languages), a graphical user interface (GUI) was developed. This GUI (see Figure 3, bottom panel) allowed students to select and start the experimental task they wanted to run by simply clicking on the appropriate button labeled with the name of the task, without having to interact directly with MATLAB code. During the Analysis sessions, students used the open source software package EEGLAB (version 13_5_4b; Delorme and Makeig, 2004) to perform the data processing steps.

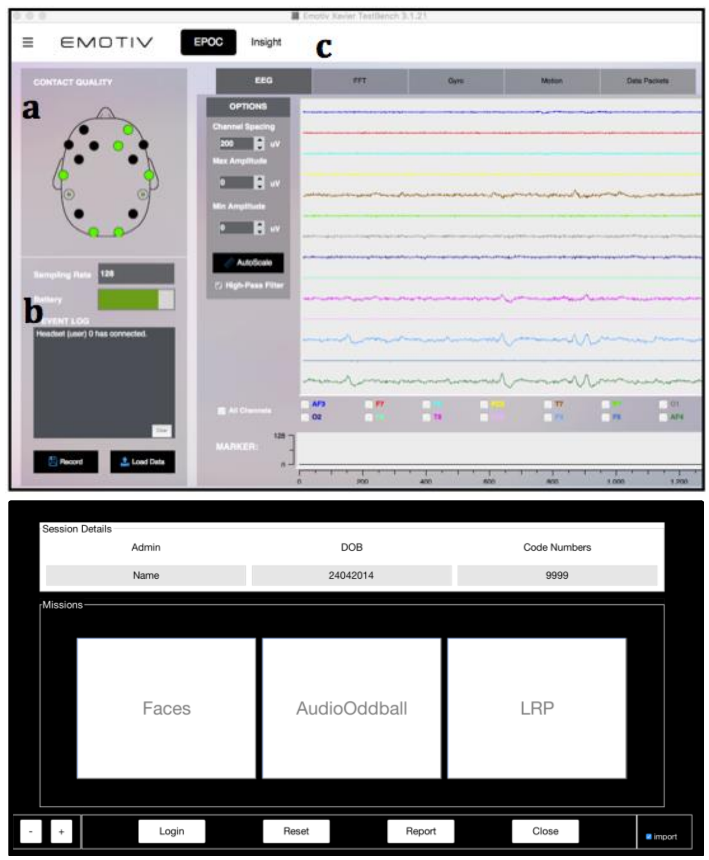

Figure 3. Top panel: Screenshot of TestBench environment; (*a*) contact quality panel, (*b*) event log panel, and (*c*) EEG display panel. *Bottom panel:* Screenshot of custom-made graphical user interface (GUI) to run the experimental tasks.

LAB IMPLEMENTATION

The EMOTIV labs were designed to complement and reinforce basic concepts introduced through more traditional modes of instruction including lectures and discussion sections. To achieve this aim, lab session topics were selected to align closely with subject matter being covered in lectures and readings in the same week. The course structure reflected the organization of the textbook used in the unit (Purves et al., 2012), and, accordingly, covered the following modules: (1) neural signaling (e.g., electrical signals, synaptic transmission); (2) sensation (e.g., the visual and auditory systems); (3) movement (e.g., motor neuron circuits and motor control); and (4) complex brain functions (e.g., attention). There was one EMOTIV lab per module, and each lab consisted of two separate sessions (a testing session and an analysis session). Labs were designed to run for 1 hour in total (the scheduled length of discussion sections at Macquarie University). Class sizes were between 25-30 students, with sufficient equipment to run the labs in small groups ($n \leq 5$).

In Lab 1 (Primer Lab), students were introduced to EEG techniques in general and the EMOTIV system in particular. This lab helped build a foundation of basic understanding of brain activity as electrical activity, which related to textbook chapters on neural signaling covered in the initial weeks of the course. It also gave students the opportunity to familiarize themselves with the EMOTIV system and its applications in neuroscience research. In Lab 2 (Vision Lab), Lab 3 (Motor Lab), and Lab 4 (Cognition lab) the fundamentals of ERP techniques and the workings of the custom-made event-marker system were covered. These "experimental" labs were explicitly designed to mimic key aspects of the experimental research process.

To illustrate how ERPs afford a useful experimental window into brain function, each lab session consisted of scaffolded activities structured around accessible and well-established experimental findings. During testing sessions, students ran simplified yet realistic versions of experiments related to the topic under discussion. In follow-up analysis sessions, students learned to apply the necessary data processing steps (e.g., applying filters, epoching data), perform simple data analyses, and critically discuss the significance of their results. To ensure the to-be analysed data demonstrated the highlighted experimental effect, previously collected data was used rather than data collected during the testing sessions. Additionally, data was partly processed before delivery to the students. Both the testing and analysis sessions required students to complete supplementary activity sheets designed to guide students through essential aspects of the research process and encourage critical thinking along the way (for more details about the structure of the testing and analysis sessions including the associated activity sheets, see the Supplementary materials).

Each EMOTIV lab highlighted contemporary research findings (as recommended by Cleland, 2002) about the brain mechanisms underlying different sensory, motor, and cognitive functions – topics aligned with lectures and readings for the course. For example, the Vision Lab focused on the visual processing of faces, which is typically marked by a face-specific response (ERP) that occurs around 170ms after stimulus onset, termed the N170 (Luck 2014; Experiment adapted from De Lissa et al., 2015). The other labs had a similar research-driven nature. The Motor lab leveraged a different ERP component – the lateralized readiness potential (LRP, see Supplementary materials) (Luck 2014; Experiment adapted from Miller, 2012) – to allow students to investigate how the brain prepares a motor response and appreciate how activity related to motor preparation is lateralized to the opposite hemisphere from the limb being controlled. The Cognition lab used different ERP components – the mismatch negativity (MMN) and P300 ERP components (Luck 2014; Experiment adapted from Badcock et al., 2013, 2015) – to deepen student understanding of the role of attention and auditory processing in the brain.

OUTCOMES

One cohort of students (n = 268) has now completed the course including all of the EMOTIV labs. To assess student perception and experience of the lab sessions, an anonymous in-class survey was administered in the last Analysis session. Only the results from completed surveys were taken into account (n = 150). The survey consisted of 14 statements and students were asked whether they agreed with the statements according to a 5-point Likert scale, ranging from (1) strongly agree to (5) strongly disagree. To discourage students from automatically selecting the same answer for every statement, the survey included both positive and negative statements (e.g., The content of the lab sessions was too difficult) so that the Likert scale responses did not have the same valence across the survey. The statements and the respective median and standard deviation are presented in Table 1.

For interpretation purposes only, the statements were grouped into three post hoc categories: "Enjoyment," "Usefulness," and "Improved understanding of neuroscience concepts and methods." Following this grouping and taking the positivity and negativity of all the statements into account, the results can be summarized in three general findings: (1) Students enjoyed the lab sessions overall; (2) students found the lab sessions useful overall; and (3) students found that the lab sessions contributed to their understanding of basic neuroscience concepts and methods.

EVALUATION AND DISCUSSION

This project demonstrates that it is possible to implement a fully functional teaching laboratory in an undergraduate neuroscience course using the latest in commercial neurogaming technology. Specifically, lab activities employing the EMOTIV can give students the opportunity to gain valuable research experience using the popular cognitive neuroscience EEG/ERP techniques. The results from in-class surveys showed that students enjoyed the interactive research-based learning activities in the lab sessions. Importantly, students also found that the lab sessions enhanced their knowledge about EEG specifically, and research in cognitive and brain sciences in general. As previously highlighted in this report, the integration of technology and research-based learning activities into undergraduate neuroscience curriculum has long been

Statements	Median	SD
Enjoyment		
I enjoyed the intellectual challenge presented during the lab sessions	2	0.98
The lab sessions were enjoyable.	2	0.90
I enjoyed the problem-based learning style used in the lab sessions.	2	0.96
Usefulness		
The lab sessions took up too much of the tutorial time.	4	1.21
I feel like I gained valuable practical skills from the lab sessions.	2	1.06
The lab sessions should be part of this unit again next year.	2	0.87
The lab sessions were a waste of time.	4	0.90
The content of the lab sessions was too difficult.	4	1.00
Improved understanding of concepts and methods		
I learned a lot about EEG as a result of these lab sessions.	2	0.86
The lab sessions clearly demonstrated the importance of EEG in Cognitive and Brain Sciences.	2	0.86
The lab sessions taught me what's involved in conducting an EEG experiment.	2	0.77
The lab sessions helped me understand the course material.	3	1.10
The lab sessions have given me a deeper understanding of what research in Cognitive and Brain Sciences is like.	2	0.94
I would have understood the course material better if we didn't have to participate in the lab sessions.	4	1.09

Table 1. Median and standard deviation (SD) of the Likert scale survey questions (n = 150). Statements were scored according to a 5-point Likert scale, ranging from (1) strongly agree to (5) strongly disagree. The order of statements in this table does not reflect the order of statements in the administered survey.

identified as a valuable but challenging endeavor due to the high technical demands and costs associated with the required research equipment (e.g., Steinmetz and Atapattu, 2010). To our knowledge, the project reported here is one of the first of its kind to offer a realistic solution to these challenges and make it feasible to create a functional EEG teaching laboratory that covers all stages of the scientific research process including data collection and analysis, and can be offered to large student cohorts. Moreover, based on student feedback, it also appears that the labs were both interesting and contributed to their understanding of subject matter covered in the course – thus successfully meeting the intended educational objectives of the labs. Compared to traditional research-grade EEG equipment, the EMOTIV is highly affordable, portable, low maintenance, and easy to use. Together, these features make it possible to create authentic research-based learning experiences in undergraduate neuroscience programs.

The rapid development of technology is opening up new possibilities in neuroscience education, especially at the undergraduate level. The current project demonstrates that the emergence of relatively inexpensive neurogaming technology is set to shape the future of neuroscience education. Providing undergraduate students with the opportunity to acquire valuable research experience using EEG techniques is now well within reach. Inspired by the successful implementation of EMOTIV technology into our first-year curriculum, we are currently envisioning ways to expand its use into more advanced coursework including a second-year course in cognitive neuroscience. We are confident that the project can provide a working template for implementing neurogaming technology in other undergraduate programs worldwide.

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