Wireless Sensors for Brain Activity

Subjects: Computer Science, Artificial Intelligence

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Over the last decade, the area of electroencephalography (EEG) witnessed a progressive move from high-end large measurement devices, relying on accurate construction and providing high sensitivity, to miniature hardware, more specifically wireless wearable EEG devices. While accurate, traditional EEG systems need a complex structure and long periods of application time, unwittingly causing discomfort and distress on the users. Given their size and price, aside from their lower sensitivity and narrower spectrum band(s), wearable EEG devices may be used regularly by individuals for continuous collection of user data from non-medical environments. This allows their usage for diverse, nontraditional, non-medical applications, including cognition, BCI, education, and gaming. Given the reduced need for standardization or accuracy, the area remains a rather incipient one, mostly driven by the emergence of new devices that represent the critical link of the innovation chain.

brain wave,EEG signals,cognition study,brain-controlled games

1. Introduction

Recent innovative technology brought in an increasing proportion of hardware to the growing market for buyers of wireless, wearable single-channel, and multichannel electroencephalography (EEG) devices; given their miniature size and reduced price, such devices may be used regularly by individuals[1]. The traditional high-quality multichannel EEG devices are commonly used in medical or research fields in hospitals and laboratories, allowing clinicians and researchers to assess neural signatures in the patients and control different functions such as motor, sensory, and cognition[2]. From a data acquisition perspective, the excitation of neurons in the brain leads to a spontaneous electrical response, which can be recorded by electrodes from an EEG device[2][3][4][5].

However, traditional EEG systems need a complex structure and long period of application time, unwittingly causing discomfort and distress on the users[6]. While they may indeed lead to noisier outputs and from narrower spectrum band(s), they also allow the continuous collection of data from regular environments, such as home or office. This allows their usage for diverse, nontraditional and non-medical applications, including cognition, brain–computer interface (BCI), and, further afield, education, gaming[7] assistance[8] and security[9]. There has been indeed a surge of interest in embedding brainwave data as an input into such applications, reflected in all segments of innovation[10][11]. A number of authors recently focused on determining how non-medical EEG can be used to enhance user interaction; this was naturally followed by manufacturers designing and building such devices, which were then integrated by developers within their applications. Given that consumer-grade EEG devices do not require standardization, unlike medical devices, as defined in EU directive 93/42/EEC (https://ec.europa.eu/growth/single-market/european-standards/harmonized-standards/medical-devices_en), and are not designed or intended to be used for diagnosis or treatment of disease, this area of research remains a rather incipient one, mostly driven by the emergence of new devices which represent the critical link of the innovation chain. In this context, the aim of this study is to provide a holistic assessment of the consumer-grade EEG devices, the success of their underlying technologies, as benchmarked by the undertaken research studies, and their integration with current application domains. Beyond establishing a reference point, this review also provides the critical and necessary systematic guidance for non-medical EEG research and development efforts at the start of their investigation.

2. Available Products

The analysis of the EEG consumer-grade devices identified several market leaders, namely NeuroSky, Emotiv and OpenBCI, that will be discussed in the following section. While they may vary in terms of specific characteristics and applications, all products have in common the objective to track brain waves and operate in the <100 Hz spectrum using various sampling rates. In addition, all products have applications for monitoring performance and are typically compatible with iOS and Android devices. The summative table of discovered products is presented in Table 1.

Table 1. Summary table of consumer-grade electroencephalography (EEG) products and built-in functionality.

Product	Sensor	Channel	Sampling Rate [Hz]	Wireless Connection	Raw data Access	Operating Time (Up to, Hours)	Price [USD]	Released
NeuroSky MindSet *,[1]	Dry	1	512	Yes	Yes	-	-	2007
Neural Impulse Actuator *	Dry	-	-	Yes	No	-	-	2008
Mindflex **,[2]	Dry	1	512	No	No	-	99	2009
Emotiv EPOC *,[3]	Wet	14	128	Yes	Yes	-	-	2009

MindWave *,2	Dry	1	512	Yes	Yes	-	-	2011
XWave headset [12]	Dry	1	512	Yes	No	-	-	2011
Necomimi **,4	Dry	1	512	No	No	-***	69	2012
Emotiv EPOC+ 5	Wet	14	128/256	Yes	Yes	6	799	2013
Melon HeadBand * [13]	Dry	3	-	Yes	-	-	-	2014
MyndPlay Myndband 4	Dry	1	512	Yes	Yes	10	219	2014
Muse 6	Dry	4	220/500	Yes	Yes	5	199	2014
OpenBCI 7	Dry/wet	8/16	250	Yes	Yes	-***	199/950	2014
Aurora Dreamband [14]	Dry	1	-	Yes	Yes	-	299	2015
Emotiv INSIGHT 6	Semi-dry	5	128	Yes	Yes	4	299	2015

Muse 2 [7]	Dry	4	256	Yes	Yes	5	239	2016
FocusBand [15]	Dry	2	128	Yes	No	12	600	2016
SenzeBand [8]	Dry	4	250	Yes	Yes	4	299	2016
MindWave Mobile [2]	Dry	1	512	Yes	Yes	8	199	2018

* Not available, ** For entertainment, *** battery powered. [1] http://neurosky.com/, [2] https://store.neurosky.com/products/mindflex, [3] https://store.myndplay.com/products.php?prod=44, [4] https://www.necomimi.com/, [5] https://www.emotiv.com/, [6] https://choosemuse.com/, [7] https://openbci.com/, [8] https://www.neeuro.com/senzeband/.

2.1 NeuroSky

NeuroSky was one of the early implementors that designed, produced, and distributed consumer-grade EEG devices on the market, starting in 2007 with a NeuroSky MindSet. The hardware was hardly practical or portable, given it was a headset with two electrodes, one on the ear of the subject as a reference frame and the other one on the forehead for signal reading. The successful release of MindSet led to the second generation of gadgets along with MindWave, MindWave Mobile, MindWave Mobile plus, and MindWave Mobile 2 (the only one still on the market). MindWave Mobile 2 appeared as an educational device and gaming application, and the key function was to monitor attention and meditation.

The devices from NeuroSky have been tested in different validation studies (Table 2). In 2016, Maskeliunas et al.[1] validated the main algorithms for monitoring attention and meditation and tested blinking recognition, concluding that MindWave can achieve only 22% overall recognition accuracy. This result is very low and shows its inability to discriminate between relaxation and focusing states. The blinking recognition algorithm provided by NeuroSky had 49.6% accuracy in the tests, which is why a gaze tracker (such as Eyetribe) would be preferable. The conclusion matches two previous studies: in [12], authors observed that MindWave had a high error rate of 43.52% when classifying whether eyes are opened or closed, while[13] identified the accuracy of blinking detection is only 40%. Despite the fact that blinking detection algorithm does not have a practical usage, the hardware by itself is effective enough, as established by Abo-Zahhad et al. by their study where was used raw eye blinking waveform MindWave created to identify person among 25 other people and achieved a 97.3% accuracy [14].

Table 2. Blinking recognition accuracy for NeuroSky device.

Study	[1]	[12]	[13]	[14]
Accuracy	49.6%	43.52%	40%	97.3%

2.2. Emotiv

Emotiv is another manufacturer of consumer-grade EEG devices, focusing on multichannel measurements with wet electrodes. Given their capabilities, Emotiv devices allow more complex tasks, such as creating and executing mental commands[15], or facial expression detection[16], 3D functional mind maps for data visualization[17]. Three Emotive systems reached the mainstream market: EPOC+, INSIGHT, and EPOC FLEX[18]. EPOC+ is a device focused on academic research, contains electrodes that are placed around the scalp and several built-in motion gyro, accelerometer, and magnetometer sensors. The company also released a cheaper alternative, called INSIGHT, with a lower number of channels, semidry electrodes, and was designed for everyday usage rather than for academic research. Finally, the lineup is completed by EPOC FLEX, a medical-grade product build with multiple sensors and other features, including a control box for wireless customization[19].

Consumer-grade products from Emotiv were used in different studies. For example, in 2013, Emotiv EPOC was used by Badcock et al.[20] to make research auditory event-related potentials (ERP) in adults and children[21]. The two studies were later followed by further ERP investigation using consumer[22] and medical[23] data acquisition procedures and equipment.

The EPOC system was repeatedly compared with medical-grade systems; Debener et al. represented some modifications to the Emotiv system and combined the hardware with a medical-grade EEG electrode cap[24] in 2012, then, in 2017, Barham et al. did the same modifications into Emotiv EPOC to evaluate it against a medical device [22]. Both ERP and MMN waveforms obtained from the Emotiv system shown similar results to the medical-grade device and to the results reaching in the Badcock et al. study[20]. The total data obtained from the modified gadget was higher than the one from the original report made by Badcock et al., mostly due to more accurate electrode placement and higher electrode quality.

Regardless of positive indications, there have also been reports about low-quality EEG data and poor performance regarding Emotiv EPOC. Duvinage studied the performance of Emotiv EPOC for P300-based applications[25][26] and against advanced neurotechnology (ANT), a medical-grade EEG system[27]. The overall performance and SNR of Emotiv EPOC were poorer than the ones produced by ANT. Similar to MindWave, the Emotiv EPOC system was used to validate attention and meditation results along with the blinking recognition[1]; Emotiv led to 75.6% accuracy for blinking recognition and 60.5% accuracy for classification of focusing or relaxing. During the tests, only a small minority of subjects have been remarked a discomfort after a long period of gadget usage, but this was mentioned before in another research[28].

To summarize, when compared to medical-grade devices in scientific research data collection, the Emotiv EPOC system faces considerable challenges in data quality, sensor location, and electrode number. While not specifically highlighted by the prior studies, Emotiv EPOC does not need a flexible EEG cap. Therefore it does not require custom fitting; also, due to its form factor, it would allow the longer subject screening. The modified Emotiv EPOC [22], which was previously mentioned, has been proven as useful and also improved regarding competing against its competitors.

2.3. InteraXon

Muse, manufactured by InteraXon, is a headband with inbuilt brainwave sensors designed to facilitate meditation. In contrast to the products from NeuroSky and Emotiv, the fitting of electrodes from Muse can be adjusted to the head of the user. The most sensitive areas of the head are located under the Muse's electrodes, which help to obtain the emotion-specific signals [29]. In addition to measuring and monitoring the meditative state of the user, Muse also has a mobile application for meditation training (https://choosemuse.com/muse-app/). Following the launch of Muse, InteraXon expanded their product range with Muse 2, which offers more features (body movement, heart rate, and respiratory rate) and a software development kit (SDK) (https://github.com/NeuroJS/angular-muse), as well as a strong open-source base in GitHub (https://github.com/kowalej/BlueMuse).

In a study aimed at evaluating their accuracy in measuring ERPs, the Muse products[30] were used to obtain N200 and P300 ERP components in the oddball visual task and stimulate positivity during a reward-learning task. The results were compared to the signals resulted from Brain Vision actiCHamp System, which is considered to be the standard medical system. The study concluded that, while the performance of the two systems was relatively similar, the actiCHamp does deliver more accurate results. In the wider domain, there is a concern about data quality that Muse's configuration may not meet the criteria dictated by the guidelines for ERP's to study cognition (which includes specific requirements for formulation of the study, subjects profile, stimuli and responses, A/D signal conversion, signal analysis, non-cerebral artifact, presentation of data, and so on)[31], requiring one nonpolarized Ag/AgCl electrode for measuring the slow changes in potential and multiple electrodes which should note overlapping ERP components, as well as an adequate rejection ratio of the amplifier. The Muse headband is fitted with conductive silicon-rubber (dry) electrodes, which should be placed in four different locations. This access, focusing on the frontal part of the head, though not comparable with other consumer-grade EEG systems, allows data collection and validation, as presented by[30] and, with some adjustments, can produce higher quality signals.

In contrast to the medical-grade devices, the method to accurately label the time of experimental stimulations has been a major concern for researchers, as event markers are often needed to be created separately. In comparison to wired connections, Bluetooth is rather unstable and can introduce random delay variations [32][33].

The EEG data acquisition by Muse was compared to few medical-grade gadgets[6]. The data obtained from Muse shows an increase in broadband power and more signals, performance, and electrode placements, suggesting lower reliability. In addition, the data displayed by Muse has poor consistency between multiple measurements for the same subjects in comparison to other products (B-Alert, Enobio, and MindWave). The reason behind the inconsistency could be due to the mobile electrodes of the headband, which can be misplaced, an issue also confirmed by the conclusions of[30].

2.4. OpenBCI

OpenBCI was introduced to the market in 2013 as open-source hardware and firmware research alternative. Unlike consumer-grade EEG products, OpenBCI hardware mostly serves as an amplifier, where the activities detected in the brain (EEG), muscles (EMG), and heart (EKG) can be measured by using the sensors equipped on the schematic OpenBCI printed circuit boards and interpreted using software named Processing. Due to its focus, OpenBCI has a limited market share and is more appropriate for users who have a background in engineering. A number of studies validated OpenBCI against traditional EEG systems. In 2016, Frey represented EEG signals obtained from OpenBCI's board versus a medical-grade EEG amplifier (g.tec g.USBamp)[34]. According to the obtained results, OpenBCI performance (measured using a combination of subjective, questionary-based, and objective, physiology-based indicators) was identical to the traditional EEG amplifier from g.tec for both P300 speller and EEG-based workload tracking by using the n-back task[35]. In a similar study[36], OpenBCI, equipped with Texas Instruments ADS1299, was compared to Compumedics Neuroscan NuAmps, a medical-grade EEG system original; the comparative analysis confirmed that the two systems produced similar results in terms of brain activity and frequency analysis. Regardless of these similarities, MRCPs are not normally benchmarked against the EEG applications, as they are designed entirely to help people with muscular disability to improve their quality of life and require movement, which can also cause incidents of cable swaying and undesirable head movements.

2.5. Other Products

Due to growing demand and rapid technology development, a wide range of non-research products were developed and released on the market. A BCI-based game controlling tool—Neural Impulse Actuator—was launched to replace the usage of a keyboard and mouse. Two other developers, X wave[12] and Melon[13], proposed products aiming to monitor user attention. More recently, a number of products appeared in the wellness industry by integrating the EEG data collection platforms: MyndPlay used NeuroSky TGAM technology to develop their headband; mostly, the company sells its apps. This application is usually used for entertainment purposes; however, it additionally touches brain training and educational areas. Aurora Dreamband[14], which is designed as a headband with built-in sensors, has the ability to detect the user's motion and track their sleep pattern. FocusBand[5] development was initiated in 2009 and finally was launched in 2016. In the beginning, the headset and app were manufactured with the goal to assist golfers to monitor and note their mental state and physical performance from the mentioned neurofeedback. To allow users to observe their performance in the working environment and sleeping condition, FocusBand expanded its targeted market of wearable headsets releasing NeuroSelf Care Business and NeuroSleep. The SenzeBand device is an EEG headband which has four channels and two reference sensors that can track the attention, focus, mental workload, and relaxation levels. Additionally, the company provides apps/games for mental training, managing stress, and keeping track of brain activities. The manufacturer of SenzeBand—Chief Scientist of Neuro—is an IEEE fellow, who as a professor at Nanyang Technological University, has been publishing numerous papers on neurofeedback/brain training game [7][37].

3. Discussion

From the analysis conducted in the previous section, we summarize the following key findings concerning the review of studies in the area of applicability the consumer-grade EEG products.

A comprehensive review was provided for the leading products, based on the existing, published research studies. Given the emphasis for these devices is placed on the application domains rather than obtaining accurate readings, information about their technical characteristics is somewhat limited, describing the measurement range rather than the sensitivity or error levels. Currently, products from the four main manufacturers, called, NeuroSky, Emotiv, InteraXon, and OpenBCI, of consumer-grade EEG devices are available for purchase. Among the four, NeuroSky products appear the most successful in seizing the market due to lower prices, simplicity, and ease of use, including a single-channel EEG sensor. Unlike NeuroSky, Emotiv devices focused on the cognition and gaming fields due to two main reasons—data collection across 14 channels and being more sensitive than NeuroSky, providing it with the ability to simultaneously examine more brain regions and signals. An interesting alternative to EEG devices has been the one provided by Muse. Primarily designed for meditation, recent Muse devices have an accelerometer, heart rate, and respiratory rate sensors built-in, all of which made the product more attractive and allowed consumers to monitor more physiological factors. Comparing to the alternative ready-to-wear devices, OpenBCI offers a less user-friendly product, which is essentially a circuit board. Its open-end design (open-source hardware, firmware, and GUI) made it very appealing for engineering-related research studies in the BCI field. The focus for OpenBCI has been indeed the acquisition and processing of signals rather than its usability. The full list of the products with their characteristics is presented in Table 1.

4. Conclusion

These low-cost devices can be counted as a tangible outcome of the advancement in medical technology and BCI, which has made a great leap into the consumer market. The lower price means increasing accessibility and realizability, which simplifies for researchers to study attention and subjects' mental state without going deeply into electronics and engineering questions. These devices may unlock several functions for public usage, be extended into education and gaming industries, but their functionality is limited in comparison to the medical-grade counterparts. Some grave disadvantages of these products from NeuroSky include low sensitivity because of the presence of a single channel in addition to inflexible location and electrode type. The EEG sensors of these gadgets responsible for reading attention and meditation conditions, due to their portability aspects, are likely to yield less accurate readings, but they can easily be adapted to evaluate student attention during a classroom or to trigger some events in the application. While NeuroSky was used in a small number of studies, its products have been used in many high-ranking publications, especially as part of educational studies. In contrast, Emotiv, with its 14 channels, brings better usage of signals while retaining its portability and was particularly preferred for validation studies. Muse is a rather new device, primarily aimed at meditation, but already being used in a wide variety of studies, especially if requiring a larger number of channels. At the opposite end of the consumer-grade product, OpenBCI has high adaptability in a circuit board, requires prior understanding of electronics, bio-signal processing, and brain anatomy/physiology, but its full functionality and open source materials permit the users to develop and expand their applications and usage more freely and flexibly. Since it can be used with standard Ag/AgCl electrodes and accommodate up to 16 channels, the highest quality signals among the consumer-grade gadgets can technically be acquired using OpenBCI.

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