Usability of Three Electroencephalogram Headsets for Brain–Computer Interfaces: A Within Subject Comparison

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Currently the field of brain–computer interfacing is increasingly focused on developing usable brain–computer interfaces (BCIs) to better ensure technology transfer and acceptance. Many studies have investigated the usability of BCI applications as a whole. Here we aim to investigate one specific component of an electroencephalogram (EEG)-based BCI system: the acquisition component. This study compares on the usability of three different EEG headsets in the context of a P300-based BCI application for communication. Thirteen participants took part in a within-subject experiment. Participants were randomly given a Biosemi, Emotiv EPOC or g.Sahara headset. After every session offline classification accuracy (efficacy) was calculated and usability factors (perceived efficiency and user satisfaction) were measured using questionnaires. The 32-channel Biosemi headset offered the highest accuracy (88.5%) compared with the 8-channel g.Sahara (62.7%) and the 14-channel Emotiv (61.7%). There was no difference in accuracy between the Biosemi and the g.Sahara when comparing the same 8 channels. The Biosemi and g.Sahara were rated as more comfortable than the Emotiv. The Emotiv was rated as best for aesthetics. System setup time was highest for the Biosemi headset when compared with the g.Sahara and the Emotiv. Without information about the effectiveness, participants preferred the Emotiv. We recommend the use of a gelled headset for applications which require high accuracy and efficiency and water-based or dry headsets when aesthetics, easy setup and fun are important.

RESEARCH HIGHLIGHTS

- This systematic within-subject study compares the usability of three electroencephalogram systems in a classical brain–computer interfaces paradigm.
- Conventional gelled electrodes were found to be more effective and efficient than water-based electrodes.
- Participants valued their appearance with the system and ease of setup higher than comfort.

1. INTRODUCTION

Brain–computer interfaces (BCI) measure brain activity and convert it into artificial output that replaces, restores, enhances, supplements or improves natural central nervous system (CNS) output and thereby change the ongoing interactions between the CNS and its external or internal environment (Wolpaw and Wolpaw, 2012). BCIs aim to provide users with a muscle-independent, brain-activity-based control over software, devices and robotics. Lately, multimodal and even multi-brain BCIs have also been proposed (Gürkök and Nijholt, 2011; Nijholt and Gürkök, 2013; Obbink et al., 2011). Many studies have demonstrated that users with and without disabilities can effectively use a BCI. However, the transfer of BCIs from the lab to the daily life of people is slow and it has been argued that BCIs need to significantly improve in terms of usability to achieve technology transfer (Blain-Moraes et al., 2012; Brunner et al., 2011; Huggins et al., 2011; Kaufmann et al., 2012; Nijboer, 2014, 2015; Nijboer et al., 2014; Zickler et al., 2013). Moghimi et al. (2012) found that most current BCI prototypes are evaluated with respect to speed and accuracy and also recommend that BCIs are evaluated with respect to usability.

Usability refers to the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use (International Organization for Standardization, 1998). Effectiveness is the accuracy and completeness with which specified users can achieve specified goals in particular environments. For example, a BCI application with the purpose of providing a communication channel for people with locked-in syndrome is effective when users can spell letters with high accuracy and complete their goal of communicating a message. Efficiency refers to the resources expended in relation to the accuracy and completeness of goals achieved. So in the context of BCI, not only speed and accuracy should be evaluated, but also the user's effort level. Satisfaction refers to the comfort and acceptability of the system to its users and those affected by its use. Therefore, BCI performance evaluation should also consider the context in which the system operates. This includes personal, relational and environmental factors (Blain-Moraes et al., 2012).

In recent years, several studies have set out to improve the usability of BCIs and to define design requirements to better ensure technology transfer and acceptance. Most effort comes from the subfield of brain–computer interfacing that aims to use BCI as an access technology for assistive technology (AT) for people with physical and communication disabilities (Nijboer et al., 2014; Riccio et al., 2015; Schettini et al., 2015; Schreuder et al., 2013; Simon et al., 2014; Zickler et al., 2011). For example, Zickler et al. performed a user-centred evaluation of the first prototype of a P300 BCI combined with commercial AT software. Four users with physical disabilities and three AT experts evaluated the usability of the commercial software

in combination with the P300 BCI. Usability was assessed after users engaged in everyday challenges (e.g. answering an email). Users indicated that effectiveness was the most important consideration for such a system. When participants considered the whole system they indicated it should be easier to operate, the hardware component should be compact and it should be compatible with a wheelchair and the environment. Kübler et al. (2013) reviewed several usability studies with end-users with physical disabilities and concluded that the biggest caveats of BCI-supported AT were: the time consuming set-up of hardware and software, the need for washing hair, the uncomfortable electroencephalogram (EEG) cap, restricted mobility when using the cap, the eye-catching look of the cap and the low speed. Other people have investigated the usability in applications such as cognitive training (Lee et al., 2013), stroke rehabilitation (Morone et al., 2015), gaming (Holz et al., 2013) and art (Munssinger et al., 2010; Zickler et al., 2013). From these previous studies, we can conclude that BCIs can be usable, even when effectiveness is sometimes moderate, but that usability issues should continue to be addressed (Kübler et al., 2013).

One aspect that users with disabilities often identify as a reason for dissatisfaction is the EEG cap that is needed to measure brain signals. They indicate that the placement of such electrodes is complex and tiresome and that the cap itself is too eye-catching (Blain-Moraes et al., 2012; Grübler et al., 2013; Holz et al., 2013; Huggins et al., 2011; Nijboer et al., 2014; Zickler et al., 2011, 2013). BCI developers are aware of this and several research groups and companies are currently aiming to develop EEG headsets that do not require the application of conductive gel, for example the EPOC from Emotiv, the g.Sahara from g.Tec, the Enobio from Starlab, the B-Alert from Advanced Brain Monitoring or the water-based electrodes from Twente Medical Systems int. Recently, a number of studies set out to investigate the usability of such commercially available headsets.

Ekandem et al. (2012) investigated the feasibility of using the Emotiv EPOC and the Neurosky MindWave in scientific research (Ekandem et al., 2012). In a systematic within-subject comparison ($n = 11$) they assessed user comfort, experiment preparation time, signal reliability and the ease of use of both headsets. Nine out of 11 participants indicated that the Emotiv EPOC was comfortable to wear, whereas six out of 11 indicated discomfort while wearing the Neurosky MindWave. This was reported to be primarily related to the pinching sensation resulting from the ear clip and the pressure of the front head sensor of the Neurosky MindWave. In addition, the time to set up the Emotiv EPOC was dependent on the length and density of participant's hair and setup was slower than for the Neurosky MindWave. This suggests that the factors hair type and hairstyle are related to ease of setup.

Mayaud et al. (2013) investigated the difference in comfort between the Emotiv EPOC and six standard silver/silver

chloride scalp discs which were traditionally attached to the head with conductive paste. Comfort was measured during setup, after 1 and after 2 h. The Emotiv EPOC was more uncomfortable than the attached disks and discomfort increased over time. Eight out of 10 participants even complained of severe pain while wearing the Emotiv EPOC. The authors conclude that Emotiv EPOC is not suited for use by people who cannot express that they have pain, such as people with anarthria. This is interesting for BCI research since people with anarthria are identified as potential target users for BCI.

Duvinage *et al.* (2013) compared the effectiveness of the Emotiv EPOC and the medical grade Advanced Neuro Technology (ANT) acquisition system in a 4-choice P300-based BCI system. It was reported that the Emotiv system was a better option in terms of price, setup process and intrusiveness. On the other hand, the ANT system was reported to be more comfortable, cheaper to maintain and more durable. Crucially, it was found that the ANT system significantly outperformed the Emotiv EPOC system in effectiveness on the BCI task in both a sitting and a walking condition. Duvinage *et al.* recommend using Emotiv EPOC only for applications where effectiveness is not critical, such as gaming and communication.

Badcock *et al.* (2013) simultaneously recorded EEGs with a traditional EEG system (Neuroscan) and the Emotiv EPOC whilst presenting 21 adults with an auditory oddball paradigm. Intra-class correlations indicated that the morphology of the late auditory event-related potentials were similar across all participants when recorded with the traditional versus the Emotiv EPOC. However, the mismatch negativity waveform was only similar in 11 out of 21 participants.

David Hairston *et al.* (2014) compared four commercially oriented EEG systems (B-Alert from ABM, Emotiv EPOC, Biosemi's ActiveTwo and QUASAR's Dry Sensor Interface) on usability and focused on five main design elements: (i) the adaptability of the system for different head sizes, (ii) the participant's rating of comfort and preference, (iii) variance in the selected scalp location for the recording electrodes, (iv) the stability of the electrical connection between the scalp and electrode and (v) the integration between the EEG system and event timing information for the cognitive tasks that they presented from a stimulus presentation computer. Sixteen participants were fitted with each of the four EEG acquisition systems on four different days and performed seven cognitive tasks. Participants preferred the approach by ABM on the B-Alert. The system was easy to apply and comfortable to wear. The authors conclude that the current wireless EEG systems still fall short of allowing comfortable, long-term wear for a variety of head sizes and hair types and recommend further refinement of designs (David Hairston *et al.*, 2014).

Taken together we can conclude that an increasing number of studies investigated factors that contribute to the usability of BCI applications in general and the usability of EEG headsets

in specific. Effective EEG headsets must have a high signal to noise ratio to ensure a high level of classification accuracy. The efficiency of a headset seems determined by the time needed to place it on one's head and the ease of application and user characteristics such as head size and hair density. Furthermore, the comfort of the headset appears to contribute to the evaluation of user experience. However, we do not know which of these factors users prioritize. Are there factors they would want to compromise on? And are there more factors that can contribute to usability of a headset? Is aesthetic design equally important to healthy users as to people with motor disabilities (Holz *et al.*, 2013; Nijboer *et al.*, 2014; Zickler *et al.*, 2011, 2013)?

This study will compare how a group of healthy participants of varying ages and educational levels assess three commercially available headsets. The three headsets considered include; a 'traditional' EEG system, using 32 active gelled electrodes manufactured by Biosemi; the EPOC system by Emotiv, which uses 14 semi-dry electrodes treated with a saline solution; and the g.Sahara system by g.Tec, a dry system consisting of eight electrodes which does not require fluid or gel. Participants will assess headsets for usability (effectiveness, efficiency and satisfaction) and aesthetics whilst conducting a classical BCI paradigm: the P300-based speller (Farwell and Donchin, 1988; Kleih *et al.*, 2010; Nijboer *et al.*, 2008; Sellers *et al.*, 2003; Sellers and Donchin, 2006; Silvoni *et al.*, 2009).

We will first discuss the headsets for their physical attributes: hardware, electronics, number of electrodes etc. We then compare the classifications rates of the systems when matched for number of electrodes and electrode locations to get an indication of the effectiveness of the BCI using the different headsets. Finally, we will consider which factors are prioritized and reported in user assessments and which headset is ultimately preferred.

2. MATERIALS AND METHODS

2.1. Participants

Thirteen healthy participants (seven males; six females) took part in the study. Participants were recruited through advertisements at the university and local supermarkets as well as through our personal network. We aimed for a group of participants with a diverse range of age, gender and education. Mean age was 43.69 ($\pm$16.43) ranging from 19 to 59 years old. Two participants had finished high school alone, two had received an intermediate vocational education, four had received higher vocational education, four had a bachelor or master degree and one had a Ph.D. All participants signed an informed consent to participate in the study prior to the experiment. Participants could opt to also sign an informed consent for the use of images and videos for dissemination purposes.

2.2. Experimental design

The experiment had a within-subject design; each participant took part in three equivalent BCI experiments using each of the different headsets. The order in which the headsets were used was counterbalanced. Sessions took place over 2 ($n = 3$) or 3 days ($n = 10$). Participants who took part in two sessions in 1 day were required to take a break of at least an hour between sessions. Before the first session, informed consent was obtained and demographical information was collected. At the beginning of each session, a headset was applied by an experienced experiment leader who recorded the time (in minutes) it took from the measurement of the head size to the moment that good EEG signals were being achieved (see definition in Section 2.3). Participants then started with the experiment.

Participants were seated in a comfortable chair ~1 m away from a computer screen that displayed a 6 × 6 matrix beneath two horizontal lines (Fig. 1). The 36 squares of the matrix contained the alphabet, the numerals 1–9, and an underscore.

Figure 1. A participant engaged in the copy-spelling task.

Characters were arranged from left to right and top to bottom. The text-to-copy (e.g. the word THE) appeared on the first horizontal line (i.e. the text-to-copy line). The character-to-attend (e.g. the letter T) appeared in parentheses at the end of the presented text. The task was to attend to the character-to-attend in the flashing matrix and count how many times it flashed. The flashes were presented in random order. For each character-to-select, 10 sequences of flashes were presented, each sequence containing 12 stimuli (one for each column and one for each row). Each stimulus flashed for 100 ms and then the screen was static for 75 ms. Thus, flashes occurred every 175 ms. Accordingly, the duration of each sequence was 2.1 s and each character selection was 21 s. Two seconds after the matrix stopped flashing the next character-to-attend appeared in parentheses at the end of the text-to-copy. The participant was then given an additional 2 s to identify the matrix location of the next character-to-attend. Thus, the period of time between the end of one character selection and the beginning of the next was 4 s. No feedback was provided to participants at any time as to whether the BCI had accurately determined the attended character in order to prevent bias in their appraisal of the headsets due to their knowledge about effectiveness. In each session, the nine words of the sentence 'the quick brown fox jumps over the lazy dog' were each presented as separate text-to-copy runs for a total of 35 character selections. A sentence was chosen for copy spelling because spelling out words is a more natural task than selecting random characters. Runs were separated by 60–120 s intervals. Each session lasted ~1 h. Immediately after each experiment participants completed the questionnaire (see Section 2.4). Finally, the headset was removed from the participant's head.

2.3. Data acquisition and description of headsets

All aspects of data collection and experimental design were controlled by the BCI2000 software system (Schalk et al., 2004). In the following sections we describe each EEG system.
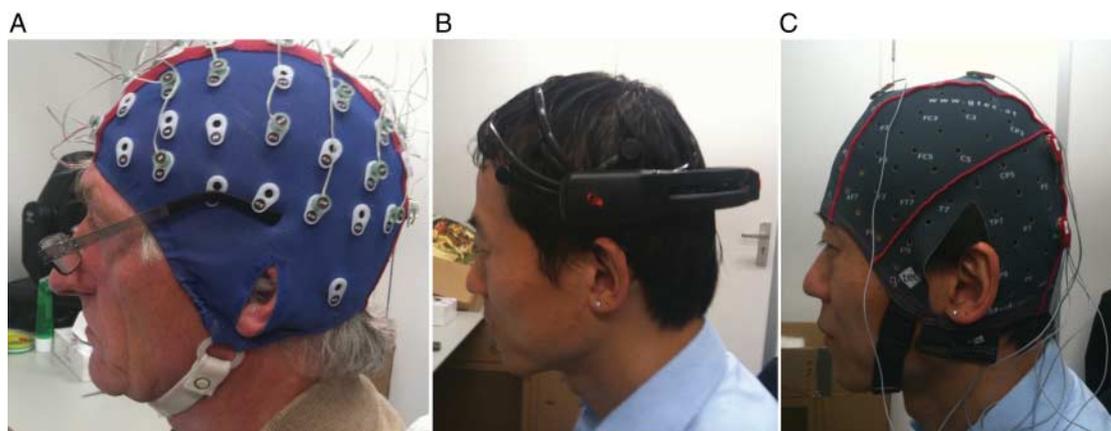

Figure 2. Participants wearing the three different headsets: (A) the Biosemi cap, (B) the Emotiv EPOC and (C) the g.Sahara cap.

2.3.1. The Biosemi system

The Biosemi headset consists of an elastic cap with plastic electrode holders that is placed on the user's head and covers the hair (see Fig. 2A). Various cap sizes are available and are designated by a colour code. The experimenter first measures the circumference of the user's head and selects the appropriate cap size. Electrode gel is inserted into the desired electrode holders with a syringe onto the scalp. Individual electrodes are inserted into the cap. Grey wires are located outside of the cap and a chinstrap holds the cap in place. The caps have ear-slits for easy access to the ears.

Biosemi's ActiveTwo amplifier uses a 2-wire active electrode system with a Common Mode Sensing and Driven Right Leg (CMS/DRL) principle. The electrodes are made of Ag/AgCl sintered material. A small printed circuit board on top of the electrode houses the first stage of the amplifier. It utilizes a 24 bit Sigma Delta Analogue-to-Digital Converter (ADC; with 19 bits effective range), with a resolution of 31 nV. The amplifier is direct current coupled, can sample at speeds of up to 16 kHz and yields a maximum bandwidth of DC—3200 Hz. Output is sent via fibre optic cable and converted to USB2 for acquisition at the host computer.

In our experiment EEG was acquired from 32 channels (FP1, AFz, FP2, F8, F4, Fz, F3, F7, FC3, FCz, FC4, C6, C2, Cz, C1, C5, TP7, CP3, CPz, CP4, TP8, P6, P4, Pz, P3, P5, PO7, O1, POz, Oz, O2, PO8). Data were band pass filtered from 0.1 to 30 Hz and a 50-notch filter was applied. The sampling frequency was 256 Hz.

2.3.2. Emotiv EPOC

The Emotiv EPOC is a black headset that—in terms of looks—might be compared with a so-called backwear audio headset. Unlike an audioset, this headset contains 16 black 'branches' that breach over a participant's head (see Fig. 2B). Fourteen of the branches contain wireless channels (gold-plated beryllium copper electrodes), while two branches have rubber endings and exist to help position the headset. Emotiv EPOC is not aligned with the 10–20 system. Instead, the manual says that the branches with the black rubber endings should be on the bone just behind each ear lobe. In addition, the manual says that 'the front sensors should be positioned 2–2.5 in. (50–60 mm or about three finger widths) above the eyebrows'.

The Emotiv EPOC makes use of an active electrode principal with semi-dry electrodes. The headset utilizes a CMS and DRL electrode much in the same way as BioSemi's ActiveTwo amplifier does. The CMS and DRL electrodes are fixed at locations P3 and P4. Other channel locations are fixed as well at: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8 and AF4. The EPOC's maximum sampling rate is 128 Hz and is alternating current coupled effectively yielding a bandwidth of 0.2–45 Hz. The signal input range is limited to 8.4 mV and utilizing a 16 bit Analogue-to-Digital-Converter (ADC; with 14 bit effective range) constituting to the smallest quantifiable difference measurable difference with the EPOC of 510 nV. It runs on a lithium polymer battery and uses a proprietary wireless protocol in the 2.4 GHz band to transmit its data to a dongle that connects to a USB2 port.

In our experiment we used all 14 channels, Emotiv EPOC's maximum sampling frequency of 128 Hz and the default band pass filters.

2.3.3. The g.Sahara from g.Tec

The g.Sahara cap is a black/grey cap that covers the hair (see Fig. 2C). The cap comes in 8 or 16 channel configurations. The g.Sahara uses a gold alloy coated multiple pin type electrode which penetrates the hair for contact with the scalp. These pin electrodes can have two different lengths. The head circumference determines which length is used. After the circumference is measured the experimenter fixes the electrode pins with the right size on the desired locations in the cap. The electrodes can be fixed at any location in the 10–20 system. Finally, the cap can be placed on a participant's head. The cap is then aligned on the head by using the 10–20 system. Grey wires are located outside of the cap and a chin strap holds the cap in place. The caps have ear-slits for easy access to the ears.

The g.USBamp has an input range of 250 mV and 24 bits of accuracy in its ADC which yields a resolution of 30 nV. The amplifier is direct current coupled and can sample up to 38.4 kHz. It is a wired system in which the cap connects to the g.Sahara box, which in turn is connected to the g.USBamp which transmits its data through USB2 to the host computer.

In our experiment EEG was acquired from eight channels (Fz, Cz, Pz, P3, P4, PO7, PO8 and OZ). Data were band pass filtered from 0.1 to 30 Hz and a 50-notch filter was applied. The sampling frequency that we used was 256 Hz.

2.4. Questionnaire

After every session participants completed a questionnaire. Participants were asked to estimate the number of minutes it took for the headset to be setup (from the moment of head measurement until the decision of the experiment leader that signals were good). They then proceeded to rate the speed of setup on a 7-point Likert scale (1 = very fast, 7 = very slow). 'Comfort' of the headset (1 = very comfortable, 7 = very uncomfortable) and ease of setup (1 = very easy, 7 = very difficult) were rated on a 7-point Likert scale. Intermediate points (2–6) were left unlabelled (see Section 4). Finally, participants were given a mirror and asked to mark their appearance with the headset on a scale from 1 to 10 (10 being the best; this marking system is typical in Dutch education and was therefore assumed to be intuitive). After every question, participants could opt to provide further comments. After the third session participants were also asked to rank each of the headsets, all of which by now they had all experienced, in order of preference.

2.5. Classification method

Stepwise linear discriminant analysis (SWLDA) was used for offline classification of the EEG data (Krusienski *et al.*, 2006). SWLDA identifies the suitable discriminant function by adding spatiotemporal features (i.e. the amplitude value at a particular channel location and time sample) to a linear equation based on the features that demonstrate the greatest unique variance. Thus, signal amplitudes at particular times and locations were considered for analysis without explicit consideration of spatial location. We used a decimation frequency of 20 Hz. The discriminant functions were derived using a total of 60 spatiotemporal features (Krusienski *et al.*, 2006) from signals recorded at all locations available on each headset.

2.6. Classification accuracy

The effectiveness of the headset was operationalized as the offline classification accuracy: the percentage of characters accurately classified by the SWLDA classifier in an offline analysis. In the offline analysis we trained an SWLDA classifier on the first 5 runs (21 characters) of each session and then classified the characters of the last 4 runs (14 characters). Mean classification accuracy across participants and session was entered into the statistical analyses.

We performed two comparisons. First, we compared the classification accuracy when the headsets were used in their optimal use (32 channels, Biosemi, 14 channels Emotiv and 8 channels g.Sahara). This comparison is scientifically unfair, but has practical value for people developing BCI applications. Second, we compared classification accuracies with the Biosemi and g.Sahara system by using the same number of channels (8) channels at the same location on each headset (Fz, Cz, Pz, P3, P4, PO7, PO8 and OZ). This comparison allows for a more direct comparison of system quality. We could not perform the same comparison with eight channels of the Emotiv, because this system does not have electrodes on the same locations as the Biosemi and g.Sahara. For one participant we could not determine weights with eight Biosemi channels due to noisy signals. Thus, this participant's

data were omitted, leaving 12 participants for the comparison of the 8-channel g.Sahara with the 8-channel Biosemi.

2.7. Statistical analysis

Since most data were not normally distributed and most variables were on the ordinal scale, we used Friedman's analysis or Wilcoxon signed-rank tests to investigate differences between headsets.

3. RESULTS

Table 1 provides an overview of the averages or medians for each dependent variable per headset.

3.1. Offline classification accuracy

Friedman's analysis demonstrated a significant effect of type of headset—when using maximum electrodes on all headsets—on offline performance ($\chi^2 = 11.091$, $df = 2$, $P = 0.004$; see Fig. 3). Wilcoxon signed-rank tests showed that classification accuracy using the 32-channel Biosemi ($88.5 \pm 18.3\%$) was higher than with the 14-channel Emotiv ($61.7 \pm 25.6\%$; $Z = -2.878$, $P = 0.004$) and the 8-channel g.Sahara ($62.7 \pm 37.6\%$; $Z = -2.567$, $P = 0.010$). There was no difference in classification accuracy between the Emotiv and g.Sahara headsets. In addition, there was no difference in classification accuracy with 32 channels ($88.5 \pm 18.3\%$) or eight channels ($79.17 \pm 25.7\%$) of the Biosemi headset for the given number of participants.

When comparing the same number of electrodes placed at the same locations on the Biosemi and g.Sahara there was *no* difference between the two headsets ($Z = -1.78$, $P = 0.075$).

3.2. Time needed to set up headset and perceived time and speed

Friedman's analysis showed a significant effect of type of headset on real time ($\chi^2 = 18$, $df = 2$, $P < 0.001$) and

Table 1. Overview of the averages or medians for all dependent variables per headset.

	Biosemi (32 channel)	Emotiv (14 channel)	g.Sahara (8 channel)
Classification accuracy	88.5% (± 18.3)	61.7% (± 25.7)	62.7% (± 37.7)
Real time to setup	20.3 min (± 6.7)	6.9 min (± 3.3)	12.1 min (± 2.9)
Participants' estimation of time to setup	14.4 min (± 5.2)	6.4 min (± 4.7)	9.7 min (± 2.9)
Evaluation of speed of setup (scale 1–7; 1 = very fast, 7 = very slow)	4	2	4
Evaluation of ease of setup (scale 1–7; 1 = very easy, 7 = very difficult)	6	3	3
Evaluation of comfort (scale 1–7; 1 = very comfortable, 7 = very uncomfortable)	3	4	3
Evaluation of appearance (scale 1–10; 1 = worst, 10 = best)	6	6	4

perceived time to set up the headsets ($\chi^2 = 13.064$, $df = 2$, $P = 0.001$). The real time to set up the 32-channel Biosemi was significantly longer (20.3 ± 18.3 min) than the 14-channel Emotiv (6.9 ± 3.3 min; $Z = -3.115$, $P = 0.002$) and the g.Sahara (12.1 ± 2.9 min; $Z = -3.182$, $P = 0.001$) (see Table 1). It also took longer to set up the g.Sahara than the
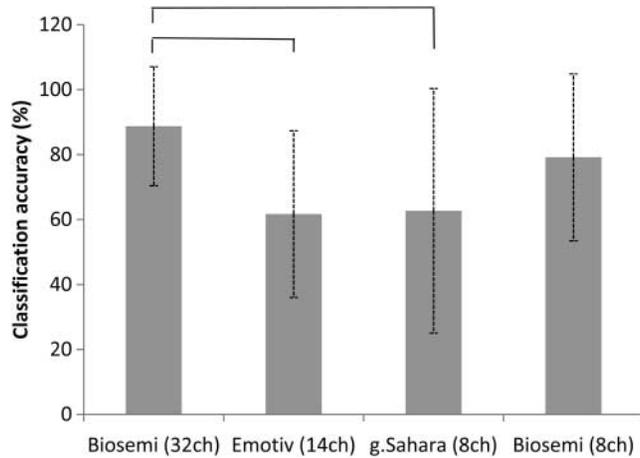

Figure 3. Classification accuracy plotted for each configuration of headset. Asterisks indicate significant differences.

Emotiv ($Z = -2.731$, $P = 0.006$). Consequently, when asked to rate the speed of setup on a scale from 1 to 7 (1 = very fast, 7 = very slow), participants evaluated the setup time for the Emotiv as significantly faster than for the Biosemi ($Z = -2.949$, $P = 0.003$) or the g.Sahara ($Z = -2.740$, $P = 0.006$). Figure 4A displays the percentage of participants that rated the time to set up the headsets as fast (score 1–3), neither fast nor slow (score 4) or slow (score 5–7). For example, 10 out of 13 participants rated the setup time of the Emotiv as fast compared with 4 for the g.Sahara and 2 for the Biosemi.

3.3. Appearance

Participants were asked to rate their appearance in each headset after looking in the mirror on a scale from 1 to 10 (10 being the best). The median rating was 6 for the Biosemi (range 1–7), 6 for the Emotiv (range 4–9) and 4 for the g.Sahara (range 1–8). Participants rated their appearance as better when wearing the Emotiv than the Biosemi ($Z = -2.814$, $P = 0.005$) or the g.Sahara ($Z = -2.911$, $P = 0.004$). There was no difference in rating between the g.Sahara and the Biosemi. When we grouped scores into satisfactory (score 6–10) or unsatisfactory (score 1–5) (see Fig. 4B), we found that 11 out of 13 participants rated their appearance as satisfactory
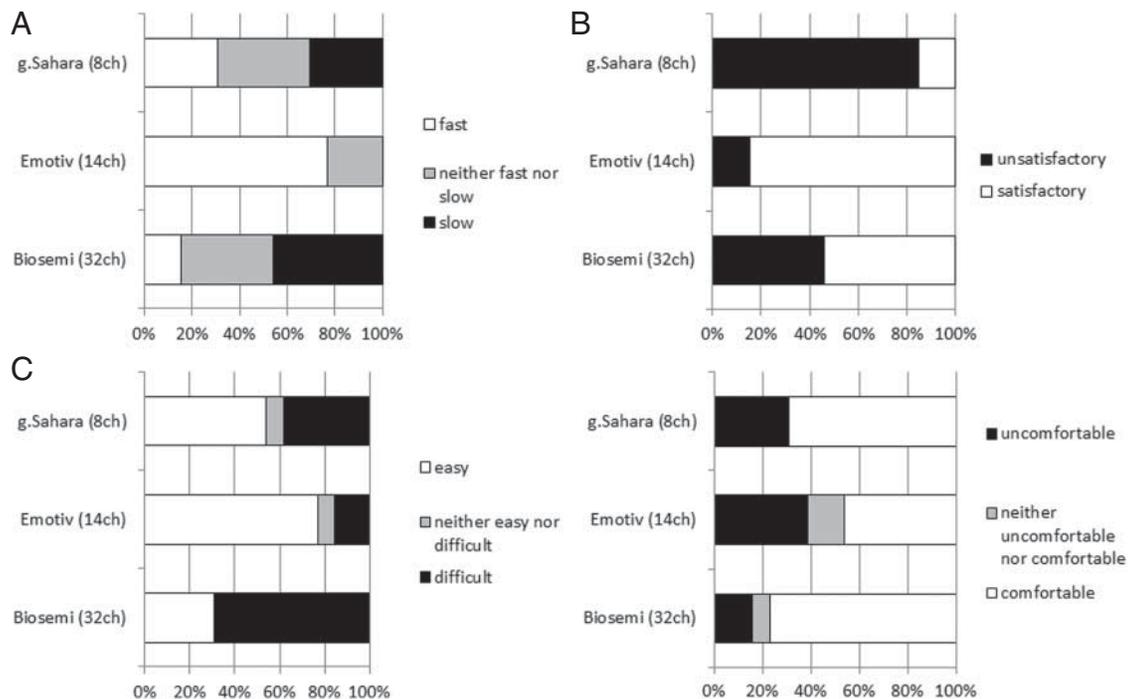

Figure 4. (A) Percentage of participants who evaluated the speed of setup as fast (white), neither fast nor slow (grey) or slow (black) depicted for each headset; (B) percentage of participants who evaluated the appearance of the headset as unsatisfactory (black) or satisfactory (white) depicted for each headset; (C) percentage of participants who evaluated the setup of the headset as easy (white), neither easy nor difficult (grey) or difficult (black) depicted for each headset; (D) percentage of participants who evaluated the headset as comfortable (white), neither uncomfortable nor comfortable (grey) or uncomfortable (black) depicted for each headset.

with the Emotiv. In contrast, 11 out of 13 participants rated their appearance as unsatisfactory with the g.Sahara. One participant commented on the difference between the Emotiv and g.Sahara: 'It [Emotiv] looks better … no flat hairdo or imprints in face like with the first [g.Sahara]'. Another participant remarked that the g.Sahara headset made him look 'comical'. The appearance with the Biosemi divided people's opinion (6 unsatisfactory, 7 satisfactory). One participant remarked that the cap made her resemble a 'swimmer'.

3.4. Ease of setup

Participants were asked to rate the ease of setup on a scale from 1 to 7 (1 = very easy, 7 = very difficult). The setup of the Emotiv was rated as easier than the Biosemi ($Z = -2.949$, $P = 0.003$) and the g.Sahara ($Z = -1.975$, $P = 0.048$). The Biosemi and the g.Sahara were rated as equally difficult to set up. When grouped into easy (score 1–3), neither easy nor difficult (score = 4) or difficult (score 4–7), 10 out of 13 participants rated the Emotiv as easy to set up, versus 7 for the g.Sahara and 4 for the Biosemi (see Fig. 4C).

Comments in the questionnaires revealed some reasons why the Biosemi and the g.Sahara were perceived as more difficult to set up. One participant rated the setup of the Biosemi as difficult, because of 'that [electrode] gel!', while another added that 'the application of gel is not very pleasant'. The Biosemi was also rated as difficult because of 'the many wires'. Indeed, if the headset is going to be used by a new user, the setup of the Biosemi and the g.Sahara requires the experiment leader to place every electrode in the cap after head measurements have been taken. One participant was certain that 'someone else should do the placement [of the Biosemi and g.Sahara], because you cannot do it yourself'. As Emotiv has all electrodes integrated in the headset another participant rated it as easy to set up: 'it is fast to put on'. A disadvantage of the Emotiv is that some sensors are located behind the ear, which may interfere with the legs of glasses. One participant commented: 'my glasses were left crooked'. A further disadvantage of Emotiv is that 'it can shift', thereby displacing the electrodes, whereas the Biosemi and g.Sahara are kept in place with chin straps.

3.5. Comfort

Participants were asked to rate the comfort of wearing the headset on a scale from 1 to 7 (1 = very comfortable, 7 = very uncomfortable). The median rating for Biosemi and g.Sahara was 5, which could be interpreted as somewhat comfortable. Emotiv was rated as neither comfortable nor uncomfortable. The Biosemi and g.Sahara were evaluated by, respectively, 10 and 9 out of 13 people as comfortable, compared with only 6 participants for Emotiv (see Fig. 4D).

The g.Sahara headset was significantly more comfortable than the Emotiv ($Z = -2.399$, $P = 0.016$). One participant remarked that she 'did not think about the headset for even one moment during the experiment'. Another added: 'you can hardly feel the headset'. Similar remarks were made about the Biosemi which was rated as equally comfortable as the g.Sahara. However, two participants—both with head sizes larger than 60 cm—experienced discomfort with the g.Sahara and Biosemi due to the pressure of the sensors. A further disadvantage of the Biosemi and the g.Sahara is the chin strap which 'is not pleasant' and 'itches'. Five participants experienced discomfort with Emotiv: 'the pressure on the head gets more annoying over time' and 'you can feel the sensors'. One of the two participants with a head size larger than 60 cm even stated that he felt 'slight pain in a couple of [localized] places'.

To sum up, the Biosemi and the g.Sahara seemed to be comfortable to wear for the majority of participants, while the Emotiv was experienced as uncomfortable by almost half of the participants.

3.6. Retakes of runs

We scored how many times we needed to repeat a run due to poor signal quality. A run was identified as poor if the SWLDA classifier could not determine a classification accuracy for that run, which occurs when the signal-to-noise ratio is very low. The official number of recorded runs should have been 117 (9 runs × 13 participants) for all headsets (see the light grey bar in Fig. 5). However, 7 runs had to be repeated while using the g.Sahara and 18 runs while using the Emotiv (see the dark grey bar in Fig. 5). Notably, all runs with the Biosemi were recorded without problems.

3.7. Preferred headset

At the end of the third session participants had experienced all headsets and were asked to rank all three headsets in order
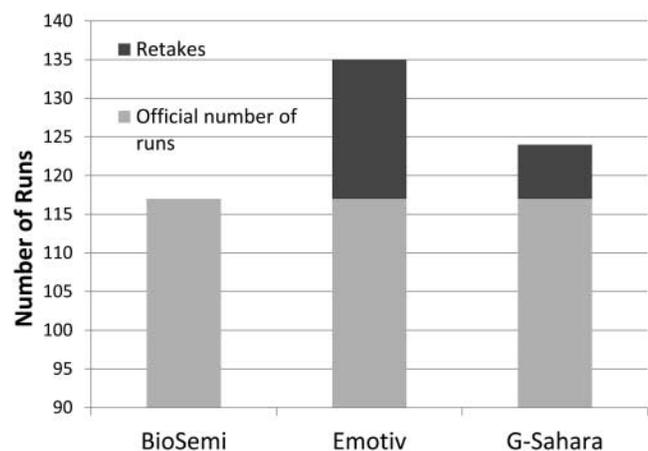

Figure 5. Number of runs that needed to be recorded for each headset. The light grey bar represents the number of runs that were planned. The dark grey bar represents the number of runs that needed to be repeated due to poor signal quality.

of preference (1 = most preferred headset, 3 = least preferred headset. Nine out of 13 participants preferred the Emotiv, while Biosemi and g.Sahara were each preferred by two participants.

4. DISCUSSION

This study set out to compare how a heterogeneous group of participants would assess three commercially available headsets in terms of usability (effectiveness, efficiency and satisfaction) and aesthetic design in a classical BCI paradigm: the P300-based speller (Farwell and Donchin, 1988; Kleih *et al.*, 2010; Nijboer *et al.*, 2008; Sellers *et al.*, 2003; Sellers and Donchin, 2006; Silvoni *et al.*, 2009). We also investigated which headset participants ultimately preferred, which factors seemed to contribute to that and how these factors weigh against each other. Finally, we compared the effectiveness (operationalized as the offline classification accuracy) of the Biosemi and the g.Sahara when matched for number of electrodes and locations of electrodes. In the following section, we discuss our findings and close by giving our reflections and recommendations on the use of headsets.

4.1. Usability

The acceptance of wearable EEG may largely depend on the usability of the sensors. A wearable EEG recording system should provide acceptable effectiveness, efficiency and user satisfaction. In this within-subject comparison we found that the Biosemi (with 32 channels) was more effective than the Emotiv (with 14 channels) and the g.Sahara (with 8 channels as expressed by the offline classification accuracies. It could be argued that the application of electrode gel provided better signal quality and hence greater effectiveness. However, when we directly compared the 8 dry-electrode g.Sahara with the same number of gelled Biosemi electrodes we found no difference in effectiveness, which is compatible with the study of Guger *et al.* (2012). Thus, we conclude that the number of electrodes mainly determined the effectiveness of the headsets and that dry electrodes can compete with gelled electrodes.

To determine how efficient the headsets were, we considered the setup time, ease of setup and the number of runs that needed to be repeated due to low signal quality. Emotiv and g.Sahara were quickest to set up, but ultimately time was lost because a number of runs needed to be repeated due to poor signal quality. In effect, sessions with Emotiv or g.Sahara were not shorter than with Biosemi. In addition, the time needed to set up the Biosemi and g.Sahara was underestimated by participants. Nevertheless, the setup of the Biosemi and the g.Sahara was perceived as more difficult than the setup of the Emotiv. From the participants' comments it seems that this appraisal was mainly due to the longer duration for electrode placement (especially for the 32 channel Biosemi) and the application of single electrodes. Headsets with integrated electrodes that do not need to be plugged into the headset and thus do not require the application of gel may be preferred by future users.

In terms of user satisfaction we found that the Biosemi and g.Sahara were perceived as more comfortable than the Emotiv. The Emotiv headset was experienced as uncomfortable by almost half of the participants, consistent with previous studies (David Hairston *et al.*, 2014; Mayaud *et al.*, 2013). This could be due to the inflexible headset that presses the sensors hard against the user's head. This result is inconsistent with Ekandem *et al.* (2012) who found that the Emotiv was mainly perceived as comfortable. However, the participants in their study wore the Emotiv only for 15 min, whereas the participants in our study wore the headset for ∼1 h. Mayaud *et al.* (2013) have also demonstrated that discomfort increases over longer time periods with the Emotiv headset. We also found that participants with larger head sizes reported discomfort with all headsets. Comments also revealed that chinstraps of the Biosemi and the g.Sahara were perceived as unpleasant and that electrodes can press uncomfortably or even become painful at certain places. We recommend that chinstraps be designed to be more comfortable or omitted altogether and that more attention be given to designing headsets for people with larger head sizes.

Another important factor contributing to user (dis)satisfaction is the appreciation of the appearance of headset. To our knowledge, the current study is the first to explicitly investigate participants' appraisal of their appearance wearing an EEG headset. Although we neglected to ask participants to rate their appearance without a headset on (which would have provided a baseline measurement), we cautiously conclude that participants did not greatly appreciate their appearance with the three headsets. However, appearance with the Emotiv was rated as better than with the Biosemi or the g.Sahara. Two explicit reasons were given. First, headsets like the Biosemi and the g.Sahara consist of a cap which covers the whole head, including the hair, which is then flattened and invisible, while the Emotiv headset looks more like a hair accessory which slides between the hair so most hairstyles would stay intact and visible. Secondly, cap-like headsets cover part of the face, which was negatively perceived by some participants in our study. Previous usability studies with people with motor disabilities consistently find that people find EEG caps too eye-catching and would appreciate a more aesthetic design (Holz *et al.*, 2013; Zickler *et al.*, 2011, 2013). We recommend that the design of headsets should aim to leave hairstyles intact and visible and avoid materials on or near the face.

To sum up, Biosemi proved to be—by far—the most effective headset in this classical P300-based BCI paradigm. Compatible with (David Hairston *et al.*, 2014) the Biosemi took longest to set up. The Emotiv and the g.Sahara were quicker to set up. However, in terms of absolute time management these two headsets were not more efficient then the Biosemi, because of lower signal quality and the fact that

a number of runs needed to be repeated. The setup of the Emotiv and the g.Sahara was perceived as less difficult. In terms of user satisfaction the Biosemi and the g.Sahara were experienced as more comfortable than the 'pressing' Emotiv by most participants. However, the Emotiv gave participants a better appearance because it did not cover the face and it left hairstyles largely intact.

How did these issues translate to user preference? In our study, almost all participants preferred the Emotiv above the Biosemi and the g.Sahara. Even though the Emotiv was experienced as more uncomfortable and the headset ultimately did not save time, it was experienced as easier to set up and less disruptive to one's appearance. Thus, we conclude that the final preference for the Emotiv of the participants in this study was based mainly on ease of use and aesthetics.

We recommend the use of a gelled headset for applications which require high effectiveness and efficiency and water based or dry headsets when aesthetics, easy setup and fun are important.

4.2. Limitations of the study

The major focus of this study was on the usability and user experience of the headsets. Since we anticipated better signal quality with the Biosemi and g.Sahara headsets, we deliberately chose not to give participants feedback on the results. This was also done because in this experimental session the effectiveness of task completion (here: to spell a sentence) did not seem to be a relevant or important goal for participants anyway. All participants could communicate verbally. Therefore, we were mainly interested in the appraisal of efficiency, user satisfaction and appearance of the headsets. However, future studies with a focus on real user applications still need to determine the trade-offs between effectiveness, efficiency and user satisfaction. We cannot exclude the possibility that (some) users would compromise on aesthetics or ease of setup for a more effective headset when the task is more relevant. For example, a long-term BCI user with Amyotrophic Lateral Sclerosis in the locked-in state reported that she did not care about aesthetic design of the EEG cap, electrodes and amplifier and rather wanted more functionality in the system (Holz et al., 2015). Users with classical or total locked-in syndrome and who have no alternative communication aid available might opt to accept effective headsets despite poor efficiency or worse appearance. Nevertheless, we anticipate that many consumers of brain–computer interfaces—able-bodied and disabled—will want to have sleek and beautifully designed headsets.

A further flaw of the current study is that the questionnaires that were used were not validated. Unfortunately, no standardized measures to assess user experience of headsets are available to our knowledge. We used conservative non-parametric tests to counter for this flaw and have interpreted our data with caution. Therefore, we feel that this exploratory study gives some insights into which factors play a role in headset usability and user experience. It should be noted that in the questionnaires we only labelled the endpoints of the Likert scale of the factors 'speed of setup', 'appearance', 'ease of setup' and 'comfort'. We did not label the intermediate responses which could have slightly biased the participants to favour the mean Frisbie and Brandenburg (1979).

A further potential limitation of this study results from a potential methodological problem with applying the g.Sahara electrodes. We were advised post hoc by the company g.Tec that a bracelet for removing electrostatic charges could to be worn around the wrist to increase signal quality. Guger et al. (2012) found higher classification accuracies with the g.Sahara. However, we cannot deduce from the methods whether the bracelet was used. They also used more sequences of flashed rows and columns which may account for the higher classification accuracies compared with our study. Nevertheless, the effectiveness of the g.Sahara may be higher when using this bracelet and future studies need to investigate this.

4.3. Future outlook and recommendations

Ideally, future wearable EEG recording systems will measure good quality signals with high reliability over time, and in diverse circumstances, with little or no effort from the user and high user satisfaction. Compatible with (David Hairston et al., 2014), our comparison of the Biosemi, the g.Sahara and the Emotiv demonstrated that users currently need to compromise on a number of these dimensions. We conclude that users prefer to compromise on comfort rather than on ease of setup and appearance. Discomfort or pain resulting from wearable EEG should nevertheless be minimized from both a point of view of research ethics and product design.

Several universities and companies are currently developing new headsets (e.g. Emotiv's Insight, Interaxon's Muse, Neuroelectric's Enobio, Wearable Sensing, DCS Corporation, National Chiao Tung University Brain Research Center) with a trend towards even fewer sensors for increased ease of setup and a more appealing design. The extent to which these headsets will accurately measure brain activity and produce good quality output remains to be seen. However, we predict the aforementioned trend will encourage general consumers to buy brain computer interfaces, especially when such trends build upon products from large companies (e.g. Walnut Wearables for Google Glass) and open source projects such as OpenBCI and 3D printing of personal designed headsets.

For the advancement of the field of physiological computing it is important to understand the factors influencing user preferences of wearable sensors. We recommend that future studies include more EEG recording devices from other companies. In addition, we recommend that more studies adopt within-subject designs, because participants can provide rich insight from their personal comparison. Interviews with open

questions and qualitative analysis may be needed to better understand individual appreciation of these systems. In addition, we would recommend that usability of such devices be assessed over longer periods to account for potential novelty effects. To properly assess efficiency, papers should include information about the necessity to repeat a run, because of poor quality. In our study users seem to determine their preference of EEG headset largely on the way they look wearing the device and the ease of use. We therefore also recommend that participants are asked to assess their appearance and are asked which headset characteristics contribute to a positive or negative appearance. Ultimately, experiments in daily life settings (e.g. at work or at a social event) may shed light on how relational factors could be related to the usability of headsets.

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