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2010 J. Neural Eng. 7 066007

(http://iopscience.iop.org/1741-2552/7/6/066007)

IOP Publishing Journal of Neural Engineering

J. Neural Eng. 7 (2010) 066007 (8pp) doi:10.1088/1741-2560/7/6/066007

Brain–computer interface using water-based electrodes

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Received 10 September 2010
Accepted for publication 5 October 2010
Published 3 November 2010
Online at stacks.iop.org/JNE/7/066007

Abstract

Current brain–computer interfaces (BCIs) that make use of EEG acquisition techniques require unpleasant electrode gel causing skin abrasion during the standard preparation procedure. Electrodes that require tap water instead of electrolytic electrode gel would make both daily setup and clean up much faster, easier and comfortable. This paper presents the results from ten subjects that controlled an SSVEP-based BCI speller system using two EEG sensor modalities: water-based and gel-based surface electrodes. Subjects performed in copy spelling mode using conventional gel-based electrodes and water-based electrodes with a mean information transfer rate (ITR) of 29.68 ± 14.088 bit min^{-1} and of 26.56 ± 9.224 bit min^{-1}, respectively. A paired *t*-test failed to reveal significant differences in the information transfer rates and accuracies of using gel- or water-based electrodes for EEG acquisition. This promising result confirms the operational readiness of water-based electrodes for BCI applications.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Brain–computer interface (BCI) systems allow people to interact with the environment through an alternative communication channel that is entirely independent of the traditional motor output pathways of the nervous system [1]. These devices may be the only possible way of communication for people with severe motor disabilities [2, 3]. Recent studies have indicated an increased interest in BCI systems that are based on various sensor modalities [4]. In non-invasive BCIs, electroencephalography (EEG) is commonly used because of its high time resolution, ease of acquisition and lower system cost as compared to other brain activity monitoring modalities [5, 6].

Nowadays, the most commonly used EEG-based BCI systems employ event-related synchronization of mu and beta bands (ERD/ERS), event-related potentials and steady-state visual evoked potentials (SSVEP) [7]. The SSVEP approach provides currently the fastest and the most reliable communication paradigm for the implementation of a non-invasive BCI system [8–10].

However, high information transfer rates are not the only essential characteristics of a BCI. In order to make BCIs more practical for a wide group of users with communication deficits in real-world settings, the BCI accessibility, flexibility and usability must be substantially improved. Currently, a non-invasive BCI setup requires unpleasant electrolytic electrode gel, causing skin abrasion by scrubbing the skin to lower the electrode impedance. In addition, this setup alone takes about 20 min. Also, after each session, at least 15 min is needed to wash the cap and the person's hair.

Since the early 1990s, many research groups have tried to avoid these inconvenient and time-consuming preparations, mainly with the development of so-called dry electrodes [11–13]. Unfortunately, there are still a lot of unsolved problems in the development and application of dry electrodes in the BCI field [14]. Since a universal solution for the use of dry electrodes for EEG acquisition is currently not available, the realistic non-invasive interface between the amplifier and the scalp of the user for BCI research is possible only with wet electrodes. A recent publication [15] presented a novel hydrogel-based preparation-free electrode for the EEG recording, which penetrates intact scalp hair and requires little or no scalp preparation procedures. This and other studies show the great interest in the continual development of a comfortable electrode interface for EEG measurement [16–18].

In this paper, we introduce new electrodes that require just tap water instead of electrolytic gel. The first prototype of these electrodes was developed by TMSi (Twente Medical Systems International BV, Netherlands). Approximately 2 years ago, TMSi started to work within the collaborative project BRAIN on the development of these novel sensors. The EU-project BRAIN (ICT-2007-224156) aims to develop practical assistive tools for users with impaired communications due to an illness or injury (e.g. brain or spinal cord injury and stroke) via BCI, which enables communication by utilizing voluntary mental activities. BRAIN aims to improve BCI reliability, flexibility, usability and accessibility while minimizing the dependence on outside help. These improvements involve upgrades to all main components of a BCI system: sensor front end/signal acquisition, signal processing and application. New water-based electrodes together with an improved amplifier technology play an important role in achieving these goals. These electrodes would make both daily setup and cleanup much faster and easier as well as more comfortable and dignified. On the one hand, the application of tap water is very tempting, rendering the clean-up procedure unnecessary. On the other hand, a lot of problems during the measurement of EEG data could be expected. The quality of the measured EEG signals should be evaluated in the real BCI application. This paper presents the first study with current implementation of water-based electrodes. It compares two types of electrode in the online SSVEP-BCI experiment: conventional gel-based and new water-based electrodes.

The paper is organized as follows. The next section describes the development of the proposed water-based electrodes for the measurement of EEG signals. In section 3, methods and materials used for the comparison of two types of electrode are presented. Finally, results from the evaluation of these two sensor modalities performed on a group of ten subjects are presented and discussed.

2. Water-based EEG electrodes

The development of water-based sensors started with initial tests of several different materials in order to estimate the stability, noise and frequency response when the material is used with tap water as the interface. During the initial investigation, several materials, such as silver, chlorinated silver, gold, tin, stainless steel, silver chloride ceramic and carbon-rubber, were tested. Large differences in material usability were found. First, the dc (direct current) offset as well as the dc drift showed large differences. Some materials, such as stainless steel and gold, were more sensitive to movement artefacts than others. Due to the very high input impedance of the EEG amplifier used (Porti 7, see section 3.3 for more details), it was possible to measure some bio-electrical signals even with dry carbon-rubber sensors, which are successfully used nowadays in combination with steep high pass filters for EMG and ECG recording of sports activities. However, the use of carbon-rubber as an interface material has a very big disadvantage as it shows a large number of movement artefacts. Even when moving the head very slowly, the amplitude of artefacts is about 2000 μV. Therefore, the initial conclusion is that carbon-rubber could be a very nice candidate for the development of dry electrodes, but the sensitivity to movement artefacts should be decreased by a factor of at least 20. Concerning the other materials, the results showed not only too high a dc offset but the dc drift as well. Therefore, a usable signal could be obtained only with the use of very steep filters (high order filters or digital filters). This is, however, not acceptable in BCI applications because of the resulting distortion in signal characteristics. For that reason, all these listed materials were rejected as candidates for the water-based electrodes.

In the next tests performed, several types of silver-chloride ceramic discs with a sponge filled with water as the interface to the skin were analyzed. The results looked rather promising as several bio-electric signals were measured with a low level of signal noise. However, this sensor still has high sensitivity to movement artefacts, although it is better than previously rejected materials. At this stage of development, the following conclusion was made: it is possible to measure EEG activities using tap water as the interface to the scalp. However, movement artefacts, mainly influenced by the shape of the electrode, remain one of the major problems.

After the described stage of development and design refining of the initial contact part of water-based electrodes based on silver-chloride ceramic discs, as shown in figure 1(a), the tests were performed using a stiff interface material, such as felt, stiff sponge, pressed wool and rolled-up cotton. The rolled-up cotton electrode is shown in figure 1(b). The signals acquired using these materials were rather stable, the noise figures were comparable, or even better than conventional EEG electrodes, and the movement artefacts were of low amplitude. The dc properties were comparable to the standard EEG electrodes and very usable for the measurement of bio-electrical signals. In this way, using a small pellet electrode and rolled in cotton, it was possible to develop a usable water-based sensor. Several tests were performed to get an impression of the sensor duration. It was tested to see how long the water-based sensor can be used. The test results showed that even after 4 h of usage, the acquired signals were still very stable and clean.

Several experiments were performed in order to develop a prototype of a head cap, in which the cotton pellet electrodes could be integrated. For the first prototype, a commercially available head cap was used to integrate the sensors. Figure 2 shows the prototypes of water-based electrodes used in the study. These were mounted in a standard housing of the head cap and could easily be used with this head cap in the usual way. Next, the prototypes of the water-based electrodes were tested in an online SSVEP experiment.

(a) (b)

Figure 1. Prototype of the water-based electrode. (a) The silver-chloride pellet electrode. (b) Stiff rolled-up cotton, using a pellet electrode.

Figure 2. The water-based EEG electrodes used in this study.

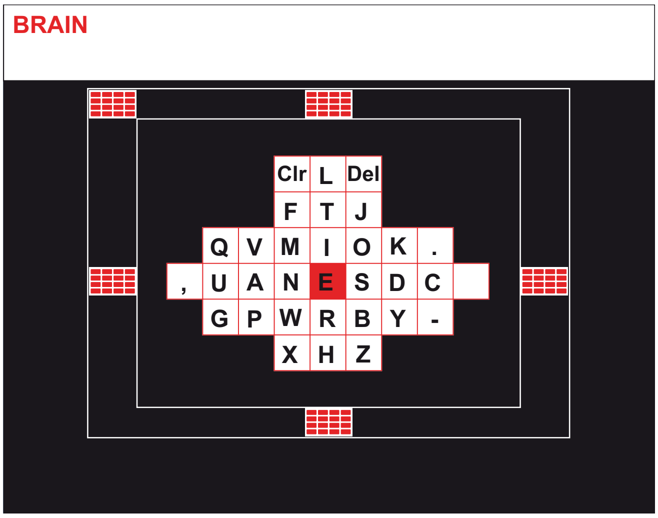

Figure 3. The display and SSVEP stimulator (custom-made frame with LED fields placed over the LCD display) used in this study. The five red blocks correspond to the LED fields. Each LED field consisted of a matrix of 4 × 4 LEDs connected in parallel.

3. Methods and materials

The protocol and materials used to compare two sensor modalities for BCIs are described in detail in this section. Normally, an EEG sensor is tested concerning its technical specifications, such as the type (active or passive, invasive or noninvasive, etc), level of noise, dc behaviour and variability, frequency response, impedance and stability of impedance, weight and wearability, and sensor material. In this study, the main focus was directed to the BCI application, quantified as conventional BCI performance in terms of information transfer rate and accuracy. In general, these parameters are highly person dependent and could be influenced by an individual's motivation, relaxation, fatigue, etc. However, this kind of test establishes a good comparison between different sensor techniques in a real-world application. The Bremen-BCI system was used to test the usability of water-based electrodes in comparison with standard gel-based electrodes. The SSVEP-based Bremen-BCI system is described below. More detail can be found for example in [19, 20].

3.1. Subjects

Ten subjects, of which seven were male and three female, participated in the study presented here. The subject's mean age was 28.50 ± 2.550 years and ranged from 25 to 33. All participants were healthy right-handed volunteers. Seven subjects needed vision correction (glasses or contact lenses) and eight subjects had used the SSVEP-based Bremen-BCI before. No subjects were excluded from the study due to their hairstyle. Experiments were carried out at the Institute of Automation of the University of Bremen in a normal office room environment with ambient light, which is different from other studies that use an electrically shielded room with low background noise and luminance. The situation when a subject uses a BCI at home was simulated. Subjects did not receive any financial reward for participating in this study.

3.2. Experimental protocol

Subjects were asked to answer screening questions regarding their age, gender, need for visual correction and handedness. After the experimenter explained the complete protocol, the subject had time to ask questions about the experiment and then was ready for EEG recording. Subjects seated in a comfortable chair approximately 60 cm from a LCD monitor, which displayed the spelling interface shown in figure 3. The SSVEP stimulator was attached to the monitor. The five red blocks correspond to the LEDs, as shown in figure 3. Each

(a) (b)

Figure 4. EEG acquisition with two different sensor modalities. (a) EEG acquisition with Ag/AgCl electrodes and conventional electrolytic gel. The electrodes and EEG cap are distributed by MedCat, Munich, Germany. (b) EEG acquisition with water-based electrodes manufactured by TMS international, Oldenzaal, Netherlands; the EEG cap manufactured by Guger Technologies, Graz, Austria.

subject completed two EEG sessions, which differed only in the sensor modality used. The sessions were randomly permuted—some subjects started with water-based and others with gel-based electrodes—in order to avoid the sequence of sessions affecting the user preference or the overall system performance. After correctly placing the corresponding EEG cap on the head of the subject, the starting time was measured. Then, EEG preparation started, which consisted of preparation of the skin, placing the electrodes on the cap, connecting the electrodes to the amplifier and visually checking the EEG signals. When the experimenter approved the quality of the EEG signals, the time was registered again and the preparation was finished. Subjects participated in a practice run and the experimenter used the resulting data to manually calibrate the BCI system with a subject-specific threshold for each frequency. Next, each subject used the SSVEP-BCI system to spell three words. These words were previously chosen by the authors to be spelled in a copy spelling mode. The three copy spelling words were 'BRAIN,' 'CORTEX,' and 'MEMORY.' The order in which these words were presented was determined randomly for each subject. The experimental protocol was strictly designed: in the case of misspelling, the participants were advised to correct errors by using the special characters 'Del' (delete the last character) and 'Clr' (delete the whole spelled text). After all words were spelled, the EEG cap and electrodes were removed. The subjects had some minutes to wash and dry their hair in the case where the experiment started with gel-based electrodes, or just to dry in the case of water-based electrodes. Then, the second session started, and the procedure was repeated for the next sensor modality. At the end of the experiment, the subject was asked about the electrode modality of their preference. The entire procedure took about 30 min on average per subject, and never longer than 40 min.

3.3. EEG recording

The EEG measurement system consists of two parts: the sensors and the bio-signal amplifier system. The cables between the sensor and the amplifier's input are extremely important. Most of the power line disturbances and movement artifacts are produced by the cables themselves. For that reason, only electrodes with shielded cables were used in this study for both sensor modalities. For the session with gel-based electrodes, EEG data were recorded from the surface of the scalp via eight sintered Ag/Ag-Cl EEG electrodes, as shown in figure 4(a). Standard abrasive electrolytic electrode gel was applied between the electrodes and the skin. An EEG head cap and a chin strap provided by MedCat (MedCat supplies, Munich, Germany) were used to fix the electrodes to the subject's head. During a standard EEG preparation procedure, it was necessary to scratch the skin to obtain impedances lower than 5 $K\Omega$. However, when using an advanced EEG amplifier (amplifier Porti7 developed by TMS international, Oldenzaal, Netherlands), the measurement of impedances was not needed. With the amplifier used, EEG signals could be measured even with impedances higher than 100 $K\Omega$. Only the ground electrode needed low impedance, but this impedance was not measured or adjusted. For the session with water-based electrodes, EEG data were recorded from the surface of the scalp over eight ceramic pellet electrodes using rolled cotton, as shown in figure 4(b). Front-end measuring was performed from dc and digitized with 22 bits, sigma delta A to D conversion, without filtering. The amplifier used had a high input impedance and active true signal shielded cables were used; the shielding was built with a carbon coating. The EEG headcap was a commercial cap provided by g.tec (Guger Technologies, Graz, Austria). The water-based electrodes were prepared by placing them into a glass with tap water for several minutes.

All of the following steps were performed in a similar way for both sensor modalities to ensure the accuracy of the comparison. For both sessions, all data were recorded from sites over the parietal and occipital cortex P_z, PO_3, PO_4, O_1, O_z, O_2, O_9 and O_{10} according to the international system of EEG measurement [21], and measured with respect to a ground electrode. The ground electrode was attached to the right earlobe using standard electrolytic gel to ensure the claimed low impedance. This choice replicated the typical grounding for the medical devices. Data were acquired and amplified through a Porti7 amplifier developed by TMS international, which included a digital recursive filter implemented in the amplifier's hardware. Porti7 records unipolar inputs configured as the reference amplifier, i.e., all channels are amplified against the average of all connected inputs. Acquired signals were transmitted to the computer by means of a bi-directional glass fibre. The amplifier was connected to the USB port of a regular dual core laptop computer running the BCI2000 [22] general software framework. This software consists of four modules: source, signal processing, application and operator. The operator used was the release provided by the BCI2000 developers; all other modules were reimplemented by the authors. The source module acquired signals from the Porti7 amplifier. These signals were digitized with a sampling rate of 256 Hz. During signal acquisition, a notch filter at 50 Hz and a high-pass filter with a cut-off frequency at 0.1 Hz were applied in the software. EEG signals were then transmitted to the signal processing module in blocks with 32 samples. The signal processing module and the application interface are the topic of the following section.

3.4. BCI system

The Bremen-BCI signal processing methodology was used to test the usability of water-based electrodes in comparison with standard gel-based electrodes in an online SSVEP spelling application. Figure 3 shows a screenshot of the display used in this study at the beginning of the spelling trial, and a graphical representation of the SSVEP stimulator. The spelling interface of the Bremen-BCI was displayed on an external LCD screen (17" LG Flatron with vertical refresh rate of 60 Hz and resolution of 1280 × 1024) and the SSVEP stimulator was attached to the monitor. The centre of the display contained 32 characters that the subject could select and thereby communicate. The top of the screen presents the text in red that the subjects had to spell and below the text in black that the subjects had already spelled. At the beginning of each run, a cursor was presented over the 'E' character in the middle of the layout. Subjects spelled letters by navigating the cursor 'left', 'right', 'up' or 'down' until the desired letter was reached. With the 'select' command, a letter was selected and displayed in black. Audio feedback followed every recognized command. After every selection, the cursor automatically moved back to the initial letter 'E'. Cursor movements could be assessed by focusing on one of five boxes presented as a custom-made frame with light emitting diodes (LED), as can be observed in figure 3. Each LED field consisted of a matrix of 4 × 4 LEDs connected in parallel. A total of five LED fields oscillated at different constant frequencies of 13, 14, 15, 16 and 17 Hz, and encoded the commands 'left', 'right', 'up', 'down' and 'select,' respectively. These frequencies, and the best arrangement of characters in the display, were determined and validated through the prior work of the authors [23, 24].

The Bremen-BCI SSVEP detection algorithm was implemented as a new signal processing module into the BCI2000 framework [22]. The SSVEP signal processing module processed incoming signals every 100 ms using a window with a segment length of 2 s. This algorithm automatically determined the best spatial filters for each subject using the methodology introduced in [19], and then calculated the signal-to-noise ratio (SNR) at each of the five stimulation frequencies. The estimated SNR for all frequencies were normalized into probabilities using a Softmax function to enhance signal classification, as described in [25]. If the probability at a specific frequency exceeded a predetermined threshold, which was previously adjusted for each subject during the familiarization run, the corresponding command was executed. A 'ResultCode' signal corresponding to the classified command was transmitted to the application interface via the UDP protocol only if 2 s had passed since the last command. The ResultCode was then mapped into cursor movements or letter selections. If a classification was performed, the EEG data of the buffer were cleaned. Additionally, all LED fields were turned off for 1 s to provide visual feedback to the user.

4. Results

Table 1 presents demographic information (age, gender) and performance results of ten subjects. Performance was measured in terms of information transfer rate (ITR) in bits per minute (bit min^{-1}) and accuracy (ACC) in per cent (%). The ITR was calculated based on the following formula [5],

$$B_t = \log_2 N + p \log_2 p + (1 - p) \log_2 \left[\frac{1 - p}{N - 1}\right], \qquad (1)$$

where p is the classification accuracy (ACC) and N is the number of targets. This led to an N of 5, based on four cursor movements and the select command. B_t was calculated in bits per trial. The calculation of the ITR in bits per minute (B_m) considered the spelling time T in seconds,

$$B_m = \frac{60}{T} \cdot B_t. \qquad (2)$$

Subjects spelled the three words in copy spelling mode using as first either gel-based or water-based electrodes and then repeated the procedure using different sensor modalities. With the standard gel-based electrodes, target words were spelled as follows: BRAIN (33.06 ± 14.570 bit min^{-1}), MEMORY (28.22 ± 13.553 bit min^{-1}) and CORTEX (27.75 ± 15.149 bit min^{-1}); whereas with the new water-based electrodes, performances were as follows: BRAIN (26.99 ± 11.844 bit min^{-1}), MEMORY (22.77 ± 9.065 bit min^{-1}) and CORTEX (29.90 ± 8.310 bit min^{-1}). A paired t-test failed to reveal a significant difference in the information

Table 1. BCI spelling performance (information transfer rate in bit min^{-1} and accuracy in %) with two sensor modalities averaged over three copy spelling words.

			Water-based			Gel-based		
Subject	Age (years)	Gender [-]	Time[a] (min)	ACC [%]	ITR (bpm)	Time[a] (min)	ACC [%]	ITR (bpm)
#1	28	M	4:10	82.38	14.10	4:43	93.80	16.10
#2	29	F	4:41	98.15	37.67	8:02	100.00	43.54
#3	27	F	4:31	95.77	25.80	6:34	100.00	34.62
#4	32	M	5:54	94.91	32.23	5:20	100.00	53.06
#5	25	M	4:13	100.00	36.78	5:28	100.00	38.40
#6	33	M	5:34	96.39	37.95	5:12	96.67	34.41
#7	26	F	6:27	92.48	22.07	4:10	90.77	22.37
#8	30	M	6:09	95.58	24.75	7:57	100.00	31.73
#9	28	M	4:21	95.45	20.10	6:35	84.76	9.68
#10	27	M	6:30	66.67	14.11	8:46	80.57	12.87
Mean	28.50		5:22	91.78	26.56	6:09	94.66	29.68
SD	2.550		0:53	10.013	9.224	1:40	7.142	14.088

[a] Preparation times in minutes.

transfer rates and accuracies of using gel- or water-based electrodes for EEG acquisition, $t(9) = 1.183$, $p = 0.267$ and $t(9) = 1.325$, $p = 0.218$, respectively.

Figure 5 shows an example of EEGs measured with two different sensor modalities. Usually the comparison of the different EEG sensors is performed by placing them a very close distance from each other during simultaneous recording [11, 12]. According to the experimental protocol of the actual experiment, we chose for comparison the time periods for the same subject spelling the same word ('CORTEX') 2 s prior to the first 'select' command classification (corresponding frequency 17 Hz). In both diagrams in figure 5, clear EEG signals are observed. However, dc-drift is clearly visible in figure 5(b), which displays the acquisition with the water-based electrodes.

5. Discussion

BCIs are a relevant and exciting topic in neuroscience and biomedical engineering. Current developments have lead to an improvement in the main components of BCIs, data acquisition and signal processing. However, in order to make BCIs practical devices for a wide group of users with communication deficits in real-world settings, the BCI accessibility, flexibility and usability must be substantially improved. The question of avoidance of inconvenient electrolytic electrode gel and shortening of BCI setup times was raised many times in recent decades in the BCI community. Unfortunately, the universal solution is still not available. Many budding developments had to be abandoned and many particular solutions for specific subtasks were presented, which are, however, unsuitable for the wide variety of BCI purposes. For example, *Popescu et al* in [14] stated the following regarding dry electrodes for motor imagery BCIs in section 3: 'Two subjects were initially tested, however due to particularly thick and full hairstyle no continuously stable signal could be extracted, and thus they were excluded from the study.' In contrast to this study, no subjects were excluded from the study presented here—all subjects who were able to use the SSVEP BCI with conventional gel-based electrodes were able to use the water-based electrodes, and vice versa. The developed water-based electrodes seem to be promising for measuring the electrical brain activity in a convenient way as they are not limited by external influences, such as the hair of subjects. There are several recent publications about the development and use of dry electrodes with promising results [26, 27]. However, the main focus of this paper lies in the test of the water-based electrodes in an online SSVEP experiment.

It is important to note that this paper presents the first study with current implementation of water-based electrodes and is not in the least pretending to be the best realization for water-based electrodes. These electrodes are still very sensitive to movement artifacts and, as shown in table 1, the accuracies achieved using water-based electrodes are often less than the accuracies reached using the conventional gel-based electrodes. Even though this paper presents new water-based electrodes, we emphasize that they are not all that is needed to make the system work. The EEG measurement system or amplifier in combination with the electrodes is very important to reach the principal goals. EEG signals have to be measured without power line interference (50 or 60 Hz), and without movement artifacts coming mainly from the cables. In this study, we applied a notch filter at 50 Hz on the BCI2000 source module to remove the power line interference. But using an advanced amplifier with high input impedance (e.g. Porti7), these artefacts are limited to a minimum, so that a notch filter is not necessary and only brings disadvantages. For future work using an amplifier with a high input impedance, such as Porti7, we recommend not applying a notch filter during EEG signal acquisition.

It was found that a ground electrode located on the earlobe was not an optimal position to reference the differences between the input signals of the instrumentation amplifier. In our case, all inputs of the multichannel amplifier are connected to the average reference (mean) of all connected electrode signals. The ground does not take part in the measurement but plays a role in the amplitude of the 50 Hz common mode signal, and so in the common mode rejection.

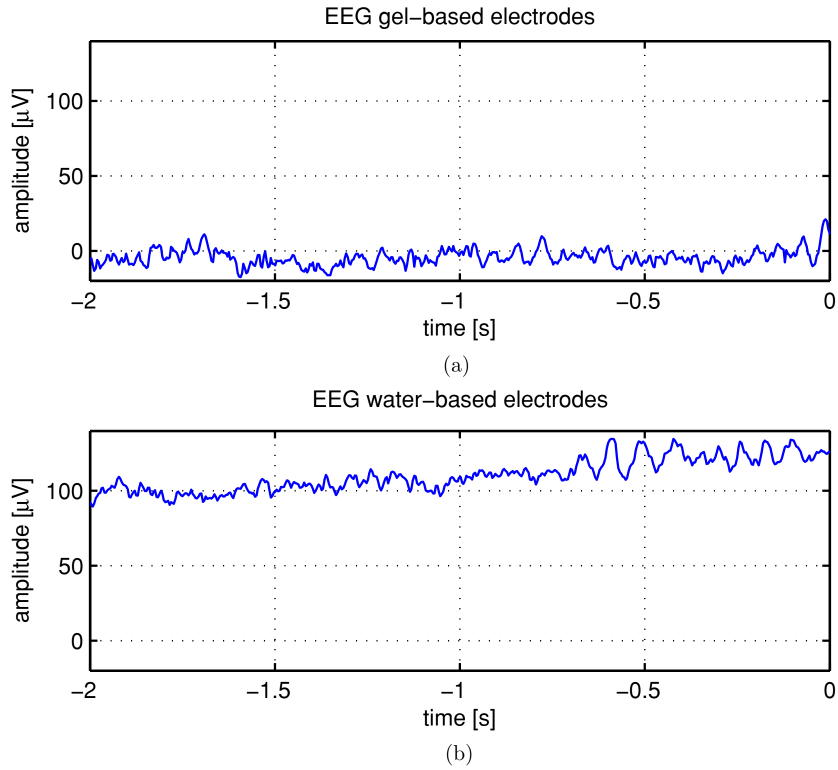

Figure 5. Example of EEG signals recorded with a (a) gel-based and (b) a water-based acquisition technique from site P_z; a high-pass filter at 0.1 Hz was applied. Signals were acquired while subject 2 spelled the word 'CORTEX'. The dc-drift is clearly visible for signals acquired with water-based electrodes. (a) and (b) The EEG signal measured 2 s prior to the first 'select' command classification.

During this study, the main focus was the comparison between the different EEG sensor modalities, rather than on the attainment of a high information transfer rate. After every command classification, all LED fields were turned off for 1.0 s as feedback for the user about performed classification and 2.0 s of data were used for signal detection. To speed up the response of the BCI system, a shorter window length could be used. We made a compromise between speed and accuracy of detection by using a window length of 2 s.

We carried out this study without any free spelling words. The reason for this is the fact that the strong comparison test in the case of the free spelling with the current letter's arrangement presented in the figure 3 is impossible as the choice of words to be spelled is very subject dependent. During our previous studies [20, 24], we realized that some users tended to select shorter words with all letters located close to the initial letter 'E' on the layout. On the other hand, other subjects were prone to select 'complicated words' with rare letters located at the layout boundaries. The chosen copy spelling words 'BRAIN', 'CORTEX' and 'MEMORY' were selected with respect to the approximate equal distribution of movement commands ('left', 'right', 'up' and 'down') needed to perform the corresponding copy spelling task.

The performance data show that using different sensor modalities, a BCI system could provide effective communication for all ten subjects. The vote for a preferred sensor modality is still bound to be subjective and the results need to undergo a detailed analysis, preferably with a larger number of subjects.

6. Conclusion and future work

In this paper, the results of the evaluation of water-based electrodes in online BCI experiments with ten healthy subjects have been presented, where the evaluation was done through a comparison with conventional gel-based electrodes. The essential characteristics of these novel electrodes are as follows:

- a rolled-in cotton connected to the small silver chloride pellet electrode (good contact impedance between materials),
- initial prototypes of water-based electrodes have been successfully embedded into electrode holders for commercially available head caps to increase the comfort of universal application and to deliver a better contact with the scalp,
- healthy users can fix the novel EEG sensors to the head cap by themselves,
- these electrodes can make daily BCI setup and cleanup much faster and easier, as well as more comfortable and dignified.

It has been shown that the signal quality of water-based electrodes is sufficient to be used in SSVEP-based BCIs. To validate the design, user tests with ten healthy volunteers using the newly designed electrodes integrated into the commercially available head cap have been performed. Sufficient signal quality was achieved—good enough for measuring a person's brain wave activity. In particular, it has been shown that:

- the EEG activity can be measured with the novel water-based electrodes,
- the differences between two sensor modalities are insignificant (a paired *t*-test failed to reveal a significant difference in the information transfer rates and accuracies of using gel- or water-based electrodes for EEG acquisition, $t(9) = 1.183$, $p = 0.267$ and $t(9) = 1.325$, $p = 0.218$, respectively).

Furthermore, to identify the main requirements for further improvement of the usability of the water-based electrode prototype, the comfort level of the use of two different sensor modalities was investigated via questionnaires. The evaluation showed that all ten subjects would prefer the novel water-based electrodes for EEG acquisition.

The following directions for further developments are envisioned:

- optimization of the electrode design and material (application for official seal 'bio-approved', lower impedance, better time characteristics regarding the duration of use without refilling or repositioning),
- design of comfortable and convenient water-based ground electrode with low impedance,
- further optimization of the amplifier front-end,
- further evaluation of the water-based electrodes for different BCI paradigms, such as P300, ERD/ERS.

Acknowledgments

The research leading to these results received funding from the European Community's Seventh Framework Programme under grant BRAIN, no 224156, from a Marie Curie European Re-Integration Grant RehaBCI, no 224753, and from the German Federal Ministry of Economics and Technology (BMWi) under Grant sBCI, 16136BG.

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