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Deliverable D2.4: Status of Dry Electrode Development Activity

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Abstract: The goal of dry electrode development activity within the WP2 is to build a dry electrode prototype for brain wave sensing that is comfortable for the user and provides sufficient signal quality. The electrodes are to be utilized in BCI applications, namely Steady-State Visually Evoked Potential (SSVEP), Event Related Synchronization and De-synchronization (ERD/ERS), and P300 based BCIs. Due to the status of the dry electrode technology and our non-encouraging results on the evaluation of the contactless dry sensors we re-focused our efforts in developing an EEG system using dry electrodes that have galvanic contact to the human scalp. The first goal we set is to reliably detect the alpha brain rhythm (brain waves in the range from 8 to 12Hz) as these brain waves are the most prominent ones in the EEG spectrum.

The outcome of the evaluation presented here is that the signal quality of dry electrodes is sufficient to reliably measure alpha brain activity. This is confirmed through user studies with the medically certified amplifier - Mobi from TMSi. However, due to the skin contact problems and high input impedance, reported in the deliverable, robustness of dry-electrode (in combination with the amplifier) has to be further improved. In particular, the dry electrode design and amplifier front end have to be further optimized.

The robustness of the dry electrode-amplifier combination has to be further improved to achieve a stable signal and reliable performance when measuring brain waves of people with long and thick hair. The following directions for further developments are envisioned:

- Optimization of dry electrode design, focusing on
    - electrode material, i.e., using “bio-approved” materials such as gold and silver/silver-chloride used in this deliverable that

will enable low impedance to the skin
    - number of pins to achieve good contact and increase the comfort
- Optimization of amplifier front-end to cope with variation in input impedance
- Optimize existing amplifier technology for usage with the developed dry electrodes.

Conclusions:

The developed dry electrodes seem promising for measuring electrical brain activity in a convenient way. The essential characteristics of these electrodes are:

- An array of metal pins embedded in conductive material to increase user comfort and to deliver a better contact with the scalp (lower contact impedance)
- Rounded pin-ends to give hair the possibility to ‘roll’ away

We have shown that the signal quality of dry electrodes is sufficient to measure alpha brain rhythm, which is confirmed with medically certified amplifier. To validate the design we performed a number of user tests using the newly designed electrodes integrated into the headset. We achieved sufficient signal-to-noise ratios, good enough for measuring a person’s brain wave activity in the alpha frequency band. In particular we showed that:

- Difference in eyes open vs. eyes closed alpha activity can be measured
- Difference in relaxed state vs. mentally active state, i.e., attenuation in the alpha frequency band (alpha de-synchronization), can be measured.

Furthermore, to identify the main requirements for further improvement of the signal-to-noise ratio and robustness of the prototype we investigated the typical impedance values for the skin-dry electrode contact during a frequency sweep (2 – 500Hz) of low voltage stimulation. The range of impedance magnitude was from few hundred kΩ to few MΩ for dry electrodes. We also discovered that typical skin electrode electrical contact properties measured on the forearm cannot be replicated at the human head, pointing to further research needed in this area.

Along with the impedance measurement we evaluate the comfort level of the electrodes. The evaluation showed that the user comfort can be impaired by the dry electrodes and that special attention has to be given to the setup of the electrodes in a headset to increase comfort and reduce obtrusiveness.

The following directions for further developments are envisioned:

- Optimization of the dry electrode design: We plan to address electrode material (keeping it “bio-approved” as in the current setup and striving for the low electrode-skin contact impedance), number of pins, design of soft reference electrodes, and evaluation if the incorporation of dry version of the ground electrode is possible.
- Optimization of the amplifier front-end: The amplifier front-end has to cope with variation in input impedance while existing amplifier technology needs to be adapted for usage with developed dry electrodes.

Our further evaluation would focus on characterizing the EEG signal obtained with dry electrodes in terms of handling noise and DC offsets. We also aim to compare the signal quality of dry electrodes to the one obtained with water (described in the deliverable D2.3) and gel electrodes when applied to one of the BCI paradigms, e.g., SSVEP. Such evaluation would provide evidence on the degree of our achievements in developing water and dry electrode sensors, and their maturity for usage in BCI applications.

Management Summary

The goal of dry electrode development activity within the WP2 is to build a dry electrode prototype for brain wave sensing that is comfortable for the user and provides sufficient signal quality. The electrodes are to be utilized in BCI applications, namely Steady-State Visually Evoked Potential (SSVEP), Event Related Synchronization and De-synchronization (ERD/ERS), and P300 based BCIs. Due to the status of the dry electrode technology and our non-encouraging results on the evaluation of the contactless dry sensors we re-focused our efforts in developing an EEG system using dry electrodes that have galvanic contact to the human scalp. The first goal we set is to reliably detect the alpha brain rhythm (brain waves in the range from 8 to 12Hz) as these brain waves are the most prominent ones in the EEG spectrum.

The outcome of the evaluation presented here is that the signal quality of dry electrodes is sufficient to reliably measure alpha brain activity. This is confirmed through user studies with the medically certified amplifier - Mobi from TMSi. However, due to the skin contact problems and high input impedance, reported in the deliverable, robustness of dry-electrode (in combination with the amplifier) has to be further improved. In particular, the dry electrode design and amplifier front end have to be further optimized.

The robustness of the dry electrode-amplifier combination has to be further improved to achieve a stable signal and reliable performance when measuring brain waves of people with long and thick hair. The following directions for further developments are envisioned:

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    - number of pins to achieve good contact and increase the comfort
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- Optimize existing amplifier technology for usage with the developed dry electrodes.

Contents

1. Introduction

The developments described in this document are part of a broader activity aiming at developing a head cap (headset) that contains electrodes for measuring brain activity in an unobtrusive and convenient way. The main requirement is that the electrodes have to provide sufficient brain signal quality, where the signal is detected using dry electrodes. Based on our previous experience with contactless dry sensors, reported in the Deliverable D2.2, we decided to focus on the development of dry electrodes that make galvanic contact to the skin. This would imply that in many cases the electrodes have to penetrate through hair. The setup is envisioned as a support for the BCI applications, namely Steady-State Visually Evoked Potential (SSVEP), Event Related Synchronization and De-synchronization (ERD/ERS), and P300 based BCIs [1]. The setup should be designed to allow setting up of the cap without expert assistance.

Currently, in the area of convenient EEG (electroencephalogram) sensing and providing feedback on brain activity, numerous predominantly game-based interfaces emerge. They use electrical brain signal to achieve communication with the environment. Examples are the interfaces provided by start-up companies such as Emotiv [2] and Neurosky [3]. These interfaces rely on specially developed caps or headsets with electrodes that are in contact with skin at the areas without hair, such as forehead and earlobes (currently first commercial products are available). On the contrary our goal was a design that can measure through hair and reliably measure brain activity. This was required as the SSVEP, ERD/ERS, and P300 based BCI applications are based on the measurement of the occipital and central brain regions where the human scalp is in most of the cases covered with hair.

As we are in the initial stage of the development of dry electrodes and as the largest changes in a person’s mental state can be associated with the presence and absence of alpha waves, we focus our evaluation mainly on the alpha frequency range. In the next step we will focus on the development of the setup with dry electrodes that can be mounted at the back of the head to cover the occipital region. This setup will be evaluated on the SSVEP BCI application developed in WP3.

1.1. Objective

In this document we present the current achievements in the development of the dry electrode headset system for measuring human brain waves.

The technical part contains description of the dry electrodes used for the EEG measurement.

The evaluation section presents the results of numerous user tests where we tried to estimate the quality of the designed prototype with dry electrodes. We used medically certified amplifiers from TMSi (Twente Medical System International) [4] for biosignal measurement. The evaluation was focused on the discrimination between relaxing and engaging mental states achieved by measuring power in the alpha frequency band.

As a step towards future developments we present the results of the impedance measurements with the developed dry electrodes. A special setup is designed for this measurement and the impedance is evaluated on a number of users. The results provide valuable information to be used for further improvement in the design of the dry electrodes as well as in the front end amplifier.

1.2. Problem description

The main challenge applying EEG electrodes is to get a good low impedance contact to the skin.

In clinical measurements this is normally done with an elastic cap with integrated Ag/AgCl coated metal cups. The skin underneath these cups is usually prepared by degreasing (IPA solution), often additional abrasion (removal of the dry top layer, stratum corneum) and applying conductive gel to reduce the impedance. This assures a low ohmic contact to the deeper skin layer (epidermis) and a ‘conversion’ from ion current in the body to electron current in the measuring system [5]. Using conductive gel also solves (partly) the problem of the varying distance between the metal contact and the skin due to the variation from person to person of the hair layer thickness.

Mounting the cap, preparing the skin, and applying gel are lengthy and cumbersome procedures that are not desired for the application of BCI technology, especially in the case of users with impairments. Current literature reports of several solutions or investigations to realize dry electrodes. Roughly two groups can be found: electrically isolated ‘capacitive’ electrodes [6] and electrodes that are in electrical contact with special structures that penetrate the stratum corneum [7] or use a free ion containing polymer or ceramic surface [8].

All these solutions still have a problem when applied onto the head with a (thick) hair layer, resulting in no contact to the skin. For example, the micro needle solution is also not ideal because of the possible irritation or even infection risk. This section documents our approach in developing a prototype system for EEG measurement that does not require skin preparation and the usage of gel and where the dry electrodes achieve direct contact to the skin but in an unobtrusive and convenient way.

1.3. Solution approach

To validate the dry electrode design we performed a number of user tests where the designed electrodes integrated into the headset.

For the evaluation of our dry electrode design we used medically certified amplifier for EEG measurements. To identify the main requirements for further improvement of signal-to-noise ratio and robustness of the prototype we investigated what are the typical impedance values for the skin – dry electrode system during a frequency sweep (2 – 500Hz) of low voltage stimulation.

The document is structured as follows. In Section 2 we give the technical details on the existing dry electrodes and the in-house developed dry electrodes with pin structure. Section 3explains experimental evaluation of the prototype with respect to the obtained EEG signal quality in the alpha band. The measurement setup and the results of the impedance measurement are given in Section 4. Discussion and future plans are summarized and the document is concluded in Section 5.

2. Dry electrode technology

This section starts with a summary of the state-of-the-art in the development of dry electrode technologies for measuring EEG. Then the proposed dry electrode design with pin structure is presented.

2.1. State-of-the-art

The document relates to the general field measuring of electrical brain activity. Existing recording electrodes can be placed into two categories of wet/gel and dry electrodes. In the following, a brief overview of existing sensor technologies for electrical brain activity is given.

2.1.1. Reusable disks cups

These are the most commonly used electrodes in clinical EEG. The materials used are tin, silver, silver/silver chloride, gold plated silver and gold. They are placed on the scalp. Conductive gel or electrolytes need to be used for effective skin contact. Typically, gel is injected under each disk through a hole in the back of the disk.

2.1.2. Adhesive gel electrodes

Adhesive gels are used both for holding the electrodes and providing electrical contact. The most common ones are disposable silver/silver chloride electrodes that are also used to record ECG and EMG signals. These electrodes are inexpensive but can only be used for recording from regions of the scalp without hair. They also require the preparation of the scalp before application.

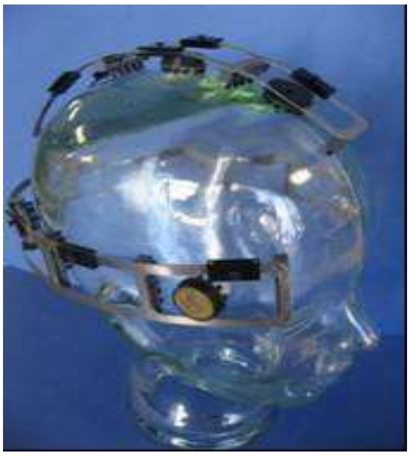
2.1.3. Subdermal needles

These are sharp wires usually made of steel or platinum. They must be sterilized before use. The most common types are single-use needles that are inserted into the stratum corneum layer of the skin. Apart from being non-practical for usage other than in clinical conditions, they are expensive as well. In the literature (including patents) these electrodes are sometimes referred to as pin electrodes (e.g. [9, 10]). However, they are not pins that are in contact with skin; rather they are spikes or pins that go through epidermis.

2.1.4. Finger/pin electrodes

In a patent [11] that describes dry electrodes the construction is based on rubber fingers with a conductive ball attached to their tip. Additionally, there is a commercially available silver-silver chloride (Ag/AgCl) dry electrode with pin structure that can be used for making contact through the hair (see e.g., http://www.electrodesales.com/el120.html). However, none of the aforementioned dry electrode designs is tested for signal quality and comfort (see Section 4 for the performed tests on Ag/AgCl electrodes).

The US based company Quasar is working on the development of “hybrid biosensor” technology [12] that is depicted in Figure 1. These sensors make contact with the scalp via a set of 'fingers’. However, contact impedance between the scalp and each finger can be as high as 10 MΩ, which is 1000 times greater than that used with conventional contact electrodes with gel. Having a couple of fingers in contact with the skin cannot reduce the impedance to the desired level. Therefore, the high capacitively-coupled non-contact electrodes (CCNE) technology has to be used in the development of the electrodes. This technology is more sensitive to movement artefacts and especially static charges in the hair. According to Quasar, the processing unit that copes with these issues is still under development.



a) b)

Figure 1. Quasar EEG measurement technology: a) quasar hybrid sensors; b) harness structure that holds the electrodes.

There are also other types of electrodes used in clinical research (e.g. nasopharyngeal, sphenoiddal, electrocortiographic balls or wicks). They are far more invasive thus are not further discussed in the document.

2.2. Dry electrodes with pin structure

For our development we wanted to have a dry electrode that has galvanic skin contact due to our previous negative experience with capacitive sensors (see Deliverable D2.2). As a starting point we took the commercially available pin-structured sintered Ag/AgCl electrodes depicted in Figure 2. Our fist evaluation showed that we were able to record the EEG signal when positioning these electrodes on the scalp near locations C3 and C4 (according to the International 10-20 system). They were able to penetrate through hair and make a contact to the skin. However, in our initial experiments the user experienced them as very uncomfortable and could not keep them on the head for the longer period of time. Therefore, we explored the possibility of developing a “more comfortable” version of dry electrodes.

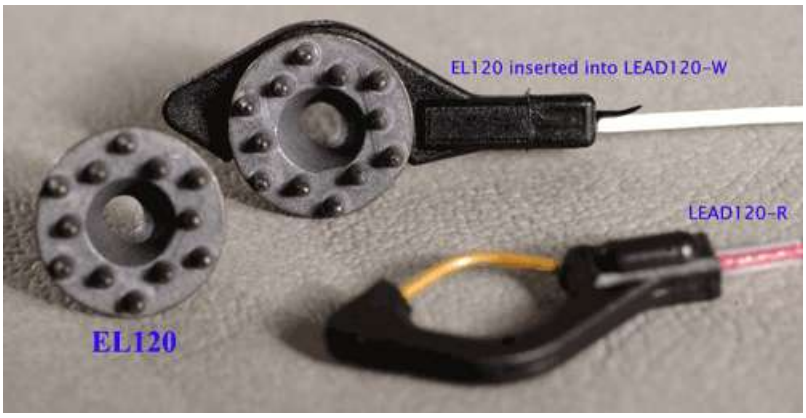


Figure 2. Commercially available sintered Ag/AgCl electrodes with pin structure.

The outcome of our efforts is presented in Figure 3. The electrode consists of a number of small gold-plated metal pins that are immersed in a flexible material containing conductive layer (see Figure 3b). The pins are rounded at the top in such a way that they exert less pressure when applied to the scalp (see Figure 3c). The length of the pins (5mm to 1cm) makes the structure largely insensitive for thicker hair layers. This is a ‘comb or brush’ principle. The rounded tips facilitate easy passing of the pins through the hair to the skin and allows the hair to roll away for better contact with the skin. With this shape there is also no irritation which may occur due to sharp edges. Because of the (low) pressure of the pins applied onto the relatively soft skin of the scalp the contact area around the tips increases. This lowers even further the contact resistance.

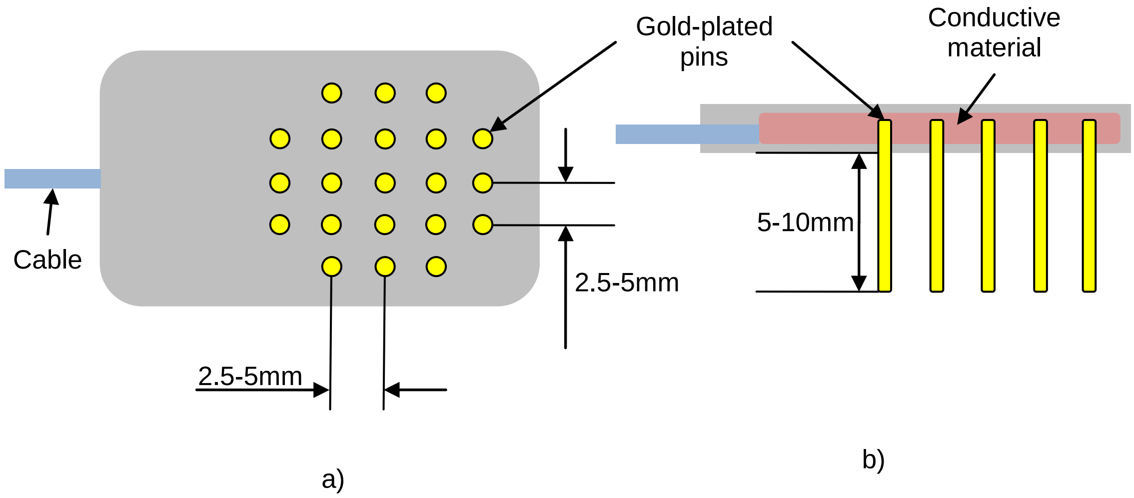


Figure 3. Schema of the developed gold-plated pin electrodes immersed in the flexible conductive material: a) Bottom view: positioning of the pins in the small support patch; b) Side view: positioning of the pins in the conductive material.

We have chosen gold plated pins to assure an inert interface to the skin without possible corrosion problems due to the salt from the sweat. Also the electrodes are can easily be cleaned as well. Gold is (like e.g. platinum) also non allergic. Other metals like nickel, chromium and copper are avoided because of health risks. Furthermore, the most used silver (with silver chloride coating) and tin electrodes have also corrosion problems.

Other contact materials that are usable are carbon and several conductive polymers but they introduce the risk to engage in the chemical reaction with the skin. Materials like stainless steel and aluminium have a natural oxide layer that reduces the conductivity to the skin. Ion containing polymers or ceramics will lose their conductivity over time and due to cleaning.

Combining gold pins with the flexible support layer containing conductive material, in the electrode design should provide more comfort to the user than the previously described electrodes. It should be also more durable, and at the same time is should provide similar signal quality. Direct comparison of the performance of these two types of electrodes (Ag/AgCl and the gold-plated ones), including the evaluation of the comfort level can be found in Section 4.

3. Reliable measurement of alpha rhythm

This section describes the evaluation of the developed dry electrodes aimed at measuring EEG in the alpha frequency range. First, the experimental setup is described, followed by the evaluation using the medically certified TMSi amplifier – Mobi [4] with the initial electrode design and head mounting, followed by a repeated evaluation with improved electrode construction and mounting of electrodes in the headset.

3.1. Experimental setup

The evaluation approach was focussed on estimating whether we can reliably detect changes in the alpha frequency band (8-12Hz). This band was chosen because the power of the brain signals in the alpha band is the most prominent in all brain regions and it is quite susceptible to person's engagement in different cognitive tasks or relaxation. For example, Figure 4 depicts the difference in the high-pass filtered (1Hz) brain signal when a person keeps his/her eyes open (top graph) and when he/she keeps them closed (bottom graph). The alpha waves are clearly visible for the eyes closed condition.

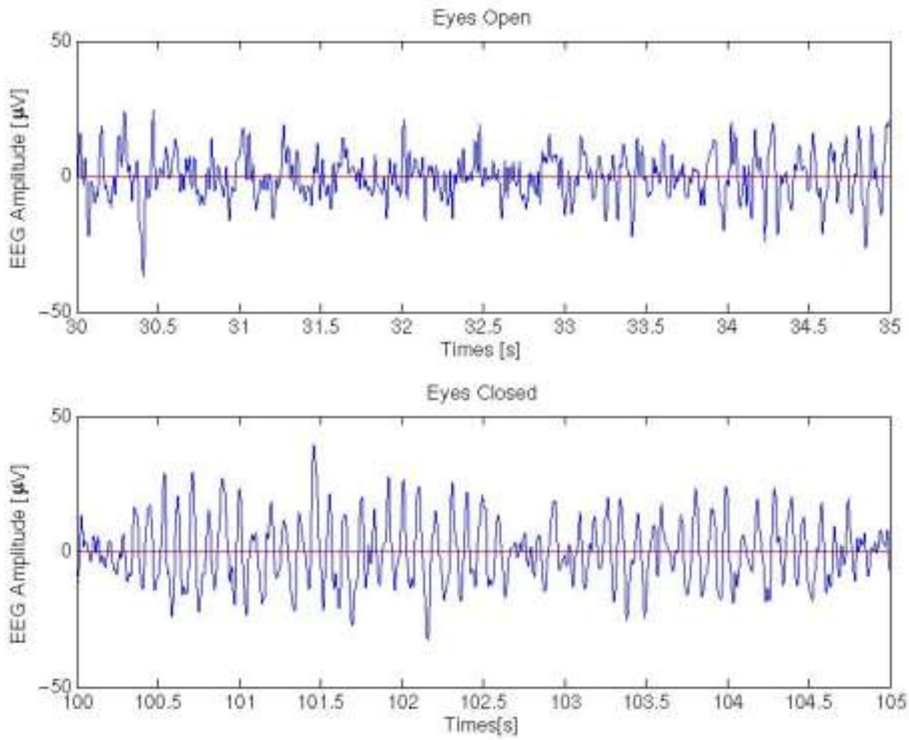


Figure 4. Example of measured EEG signal (high-pass filtered with 1Hz). The top graph shows EEG measured during eyes open and the bottom graph shows the EEG during eyes closed. Alpha activity is clearly visible on the bottom graph.

The electrodes are positioned at locations C3, C4, T3, and T4 of the International 10-20 system of electrode placement. They are used for differential measurement, i.e., we use the term reference electrodes to denote electrodes placed at positions T3 and T4 and measurement (scalp) electrodes to denote electrodes placed at positions C3 and C4. In all settings, a ground electrode is required for differential measurement (typically placed away from the other electrodes). The cabling is done using shielded cables that connect the dry electrodes with the amplifier.

For the evaluation of the signal quality with the Mobi amplifier the following setup was used. The electrodes on a headset were connected through the shielded cables to the input of the Mobi amplifier depicted in the Figure 5a. A separate shielded cable was used for the ground electrode that was mounted behind the earlobe. The amplified signals from the Mobi are sent via Bluetooth connection to the portable Nokia N800 device (see Figure 5b), where the in-house developed software was used to display and record the signals. The sampling rate of 512Hz is used. The signal analysis was done off-line on the recorded data.

a) b)

Figure 5. Illustration of the measurement setup: a) TMSi Mobi system used for EEG signal acquisition; b) Nokia N800 used for displaying the signal and signal analysis.

The evaluation itself included tests on six participants in the first and five in the second test set. We performed an evaluation of the signal quality in the alpha band obtained with the Mobi amplifier.

A typical user test started with the introduction part where the stages and the purpose of the experiment were explained to the participant. Then the prototype headset was mounted on the participants head and adjusted such that the signal quality was sufficient enough for measurement. The sufficiency is estimated by a visual inspection of the brain signal on a display and by probing the effects that teeth squeezing and closing the eyes had on the signal. In some cases and especially for participants with longer and/or thicker hair the experiment was performed even if the signal quality was questionable.

3.2. Initial evaluation with the Mobi amplifier

In the first evaluation not much effort was put in constructing the headsets for the measurement besides ensuring that is comfortable for the evaluation and that we could obtain the EEG signal in our initial tests. The electrodes were attached to a head-strap in such a way that they are comfortable to wear for the user. For the ground electrodes used in the amplifier a disposable adhesive gel Ag/AgCl electrode was selected and it is mounted behind the right earlobe. The choice replicated the typical grounding of the medical devices. The output of the measurement was two differential signals measuring the amplitude difference between the C3 and T3 electrodes and between C4 and T4 electrodes.

3.2.1. Evaluation protocol

The brain signal recording consisted of two measurement stages. In the first measurement stage the difference in the alpha band with closed and open eyes was evaluated. The recording was done such that the user first had to sit still and avoid any head movements for a period of a 90s.

In the first 30s the participant had to keep his eyes opened, in the next 30s he/she had to keep his/her eyes closed, and in the last 30s he/she had to keep his/her eyes open. This test was repeated three times.

In the second measurement stage the eyes open and eyes closed conditions were compared against a mental task that is performed with eyes closed. The mental task consisted of non-trivial multiplication of two two-digit numbers where the result of the multiplication was greater than 500, e.g., 37 times 19, 51 times 27. The recording was done such that the user first has to sit still and avoid any head movements for a period of about 150s. The recording segments were as follows: eyes open for 30s, eyes closed and no mental task for 30s, experimenter says the two numbers the participant has to multiply (while still keeping his/her eyes closed) – approximately 10s, eyes closed and mental calculation performed by the participant for about 20 to 50s depending on the task and until the participant says he/she finished the calculation, and eyes open for 30s. The procedure is depicted in Figure 6 and was repeated three times where each time different numbers were used in multiplication.

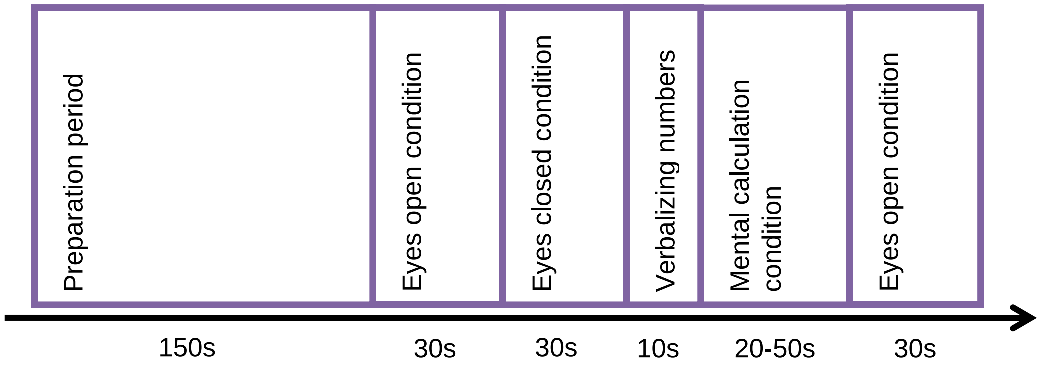


Figure 6. The evaluation protocol that includes the mental calculation task.

According to the specification, the Mobi amplifier can handle input impedance of more than 1TΩ, while the input common mode range is from -2 to +2V and the gain is 19.5. However, if the impedance is higher than a certain level (estimated to 500kΩ) the device switches off that particular channel, which we also experienced in our experiments (see below).

Six participants took part in the experiment and signed the informed consent. In the evaluation half of the participants were excluded as the measurement could not be performed. High value of the input impedance that could not be handled by the amplifier was the main reason for stopping the tests. This situation happened for participants with long but also with quite short hair. In selecting the participants we excluded the ones with long and thick hair due to cumbersome procedure we experience in the initial prototype testing, which was required to get sufficient signal quality.

3.2.2. Evaluation results

The recorded signal is analysed for each participant by estimating the power spectrum in each of the mentioned segments, i.e., eyes open, eyes closed without mental activity, and eyes closed with mental activity. To avoid transients, samples 5s prior and after closing and opening the eyes were removed from the analysis. The results are shown in the following sections.

We were able to obtain the measurement data in roughly 50% of the trials. The data in these trials was analyzed with respect to its spectral content, where special attention was paid to the alpha frequency band. Figure 7 illustrates the comparison of power density spectra for the left (C3 – T3) and right (C4 – T4) channel. A significant difference in the spectral content can be seen between the eyes open condition (blue line), and eyes closed without mental computation condition (green line). Furthermore, in most cases the difference between eyes closed with and without mental computation (red line) could be found. These differences are visible in the spectral peak as well as in the overall energy level in the alpha frequency range.

To characterize the outcome of the evaluation we summarized the ratio of the spectral power in the alpha frequency band vs. the spectral power in the 4-40Hz frequency band. The results, shown in Table 1, clearly indicate that the mental states can be distinguished using the developed prototype with dry electrodes and the Mobi amplifier, but only if we are able to achieve good skin-electrode contact.

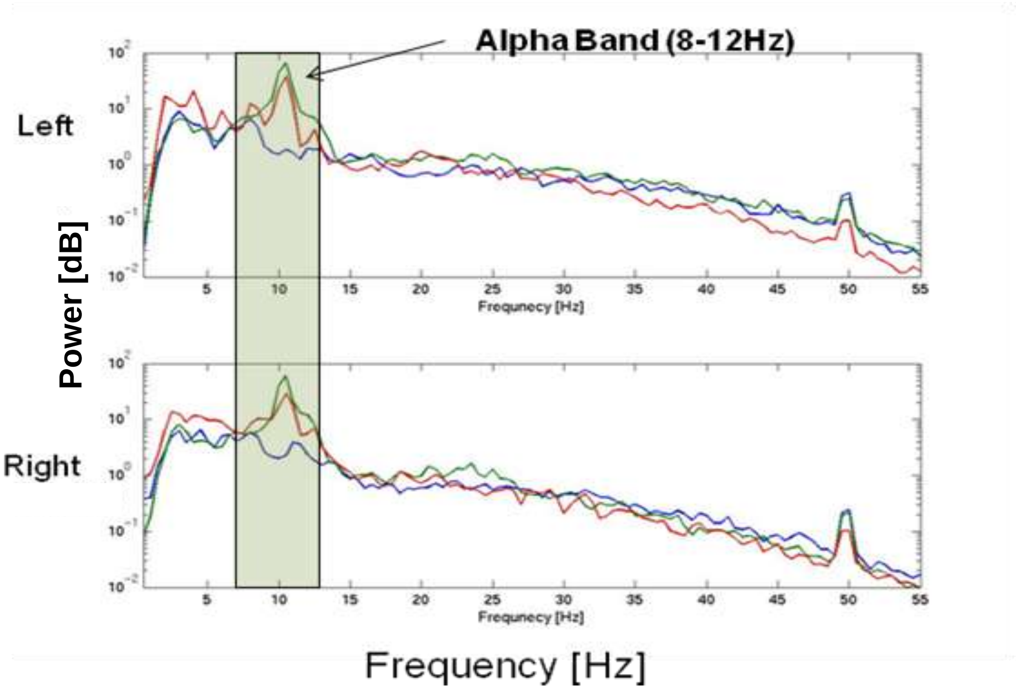


Figure 7. Power density spectra for left (C3 – T3) and right (C4 – T4) channel measured for different mental states band pass filtered in the 1-60Hz range. The blue line represents eyes open segment, the green line represents segment of eyes closed without mental computation, and the red line represents segment of eyes closed with mental computation.

Table 1. Changes in the alpha power spectral density vs. 4-45Hz power spectral density ratio. These results were obtained on three subjects and averaged over left and right channel.

Mental task	Alpha power ratio (8-12Hz vs. 4-45Hz) and
Eyes open (relax)	0.22
Eyes closed without mental computation	0.60
Eyes Closed with mental computation	0.45

The main issue was that for some of the participants we could not achieve a good signal. Bad contact, due to the amount of hair and insufficient pressure to the electrodes, and inability of the amplifier to handle high input impedance were the main causes of such problems. Since we decided to stick to the same amplifier we focussed on improving the setup with dry electrodes in order to ensure the contact for the second stage of the user evaluation.

3.3. Second evaluation with the Mobi amplifier

In the second evaluation we carefully constructed the setup of the electrodes to remain comfortable for the subjects, to improve the contact to the skin, and to improve the signal quality. Subjects had to adjust the headset themselves, unlike in the previous evaluation where we ensured that we get the best possible signal quality.

The output of the measurement was in this case two channels measuring the amplitude difference. The first one was measuring the EEG signal using gel electrodes: cup AgCl electrodes with gel mounted on the C3 location and adhesive gel patch electrode mounted at the left earlobe. The second one was measuring EEG signal using dry electrodes: the signal difference between the dry electrode positioned at C3 location and dry electrode positioned at the left earlobe. Both pairs of electrodes are positioned as close to each other as possible but taking care that there was no galvanic contact between them. For the ground electrode we used disposable adhesive gel Ag/AgCl electrode is selected and it is mounted behind the right earlobe.

Here we first describe the evaluation protocol. Then the result of the comparison between the wet and dry electrodes is presented, followed by the analysis of the alpha waves with both electrode types.

3.3.1. Evaluation protocol

The evaluation protocol was similar as for the previous evaluation. The duration of the experiment was 30 minutes and consisted of the following parts:

1) Preparation period where the experiment is explained to the participant (5 minutes)

2) Comparing the performance of the gold-plated dry electrode prototype to the 'wet' electrodes, attached to the TMSI Mobi amplifier (25 minutes)
   a) Subject puts on the headset with dry electrodes with electrodes positioned at C3 and at the left earlobe (~30s)
   b) Two 'wet' electrodes are positioned near the dry electrodes at the subjects head, and a patient ground electrode is positioned below the neck. All electrodes are attached to the TMSI Mobi amplifier (2 minutes)
   c) The stability of the signal is controlled and the electrode contacts are adjusted if necessary (<60s)
   d) The following measurement procedure is repeated 3 times (8-10 minutes):
      i) Measurement of ongoing brain activity with eyes open (30s)
      ii) Measurement of ongoing brain activity with eyes closed (30s)
      iii) Measurement of ongoing brain activity with eyes open (30s)
      iv) The subject closes his eyes and he/she is given the mental task (i.e., multiplication of two two-digit numbers) (~15s)
      v) Measurement of ongoing brain activity while the subject performs the mental task with eyes closed (<60s)
      vi) Preparation for the next experimental stage (30s)
   e) Measurement of ongoing brain activity while subject presses a button (connected to the TMSI Mobi amplifier) every 3-4s for the period of 5 minutes (6 minutes)

f) Measurement of ongoing brain activity while subject squeezes his teeth 5 times for 5 seconds interspersed with 5s brake after each squeezing action (60s)
g) Measurement of ongoing brain activity while subject performs left-right head movements 5 times for 5 seconds interspersed with 5s brake after each movement (60s)

3) Possibility to provide general remarks

Five participants signed the informed consent and participated in the evaluation. In all cases we were able to obtain high-quality signal after a shorter period of time than in previous evaluation (monitored by visual inspection of the EEG signal), and without helping participants in the setup.

3.3.2. Comparison of dry electrode and gel electrode EEG signal

As a first step in the EEG signal analysis we looked at the difference between the signals obtained with gel electrodes and the one obtained with the dry one. We computed the correlation of the EEG signal band-pass filtered in the 2-35Hz range and the EEG signal band-pass filtered in the 8-12Hz range (alpha waves). The average correlation values for each participant (averaged over three trials), along with the standard deviations of the correlation are given in Table 2 and Table 3. The correlation is estimated for all three trial conditions, eyes open segment, eyes closed segment without mental task, and eyes closed segment with mental task.

Table 2. Correlation of the EEG signal measured by dry and wet electrodes, band-pass filtered in the 2-35Hz frequency range.

Subject	Eyes open	Eyes closed (no mental task)	Eyes closed (mental task)
Subject 1	0.627 ± 0.055	0.655 ± 0.067	0.646 ± 0.147
Subject 2	0.666 ± 0.164	0.748 ± 0.126	0.671 ± 0.139
Subject 3	0.619 ± 0.083	0.756 ± 0.019	0.632 ± 0.087
Subject 4	0.569 ± 0.092	0.655 ± 0.019	0.621 ± 0.069
Subject 5	0.414 ± 0.100	0.513 ± 0.172	0.373 ± 0.098
Overall	**0.579 ± 0.127**	**0.665 ± 0.124**	**0.588 ± 0.147**

Table 2 shows the moderate correlation (between 50 and 70%) between the EEG signal measured with dry and wet electrodes in the 2-35Hz frequency range for eyes open and eyes closed with mental task condition, and moderate to high (between 70 and 90%) correlation for eyes closed without mental task condition. Moderate correlation can be caused by the different position of the electrodes on a person's scalp, but also due to the different signal range of the EEG measured by dry electrodes to the one measured by the wet ones. However, we suspect that the major cause of EEG signal difference is the presence of artefacts in the signal, e.g., ocular artefacts, head movements, and jaw movements, which have more influence on the signal when measured with dry electrodes. Changes in the skin – electrode contact, i.e., pressure and contact surface, have significant impact on the amplitude of the acquired EEG signal.

Table 3. Correlation of the EEG signal measured by dry and wet electrodes, band-pass filtered in the 8-12Hz frequency range.

Subject	Eyes open	Eyes closed (no mental task)	Eyes closed (mental task)
Subject 1	0.710 ± 0.083	0.858 ± 0.049	0.737 ± 0.105
Subject 2	0.674 ± 0.227	0.808 ± 0.111	0.679 ± 0.211
Subject 3	0.691 ± 0.188	0.937 ± 0.027	0.823 ± 0.039
Subject 4	0.622 ± 0.127	0.833 ± 0.018	0.778 ± 0.068
Subject 5	0.465 ± 0.108	0.749 ± 0.184	0.441 ± 0.143
Overall	**0.632 ± 0.161**	**0.837 ± 0.106**	**0.691 ± 0.176**

Table 3 depicts the EEG signal correlation in the alpha frequency band. Higher correlation, especially for the eyes closed condition without mental task, supports our hypothesis that the artefacts are an important factor that deteriorates the signal quality with dry electrodes. In this case for the eyes closed condition without mental task the correlation is even very high (more than 90%) for Subject 3. Such high correlation indicates that we should not expect large difference in the estimation of the relative alpha level with gel electrodes compared to the dry ones, if the person is avoiding movements during the recording session. During all our evaluation procedures we asked the participants to restrain from movements. However, these instructions were not always followed.

To further illustrate the difference of the EEG signal measured with dry and wet electrodes, we displayed part of the EEG signal (4s) from one of the subjects, using dry electrodes (blue line) and wet electrodes (green line) in Figure 8. The top figure presents the signal band-pass filtered in the 2-35Hz range, and the bottom one band-pass filtered in the 8-12Hz. We can see that in both cases there is a good match between the signals obtained with dry and wet electrodes. This indicates that measuring the alpha waves of the person can be done with dry electrodes. That is what we address in the following section.

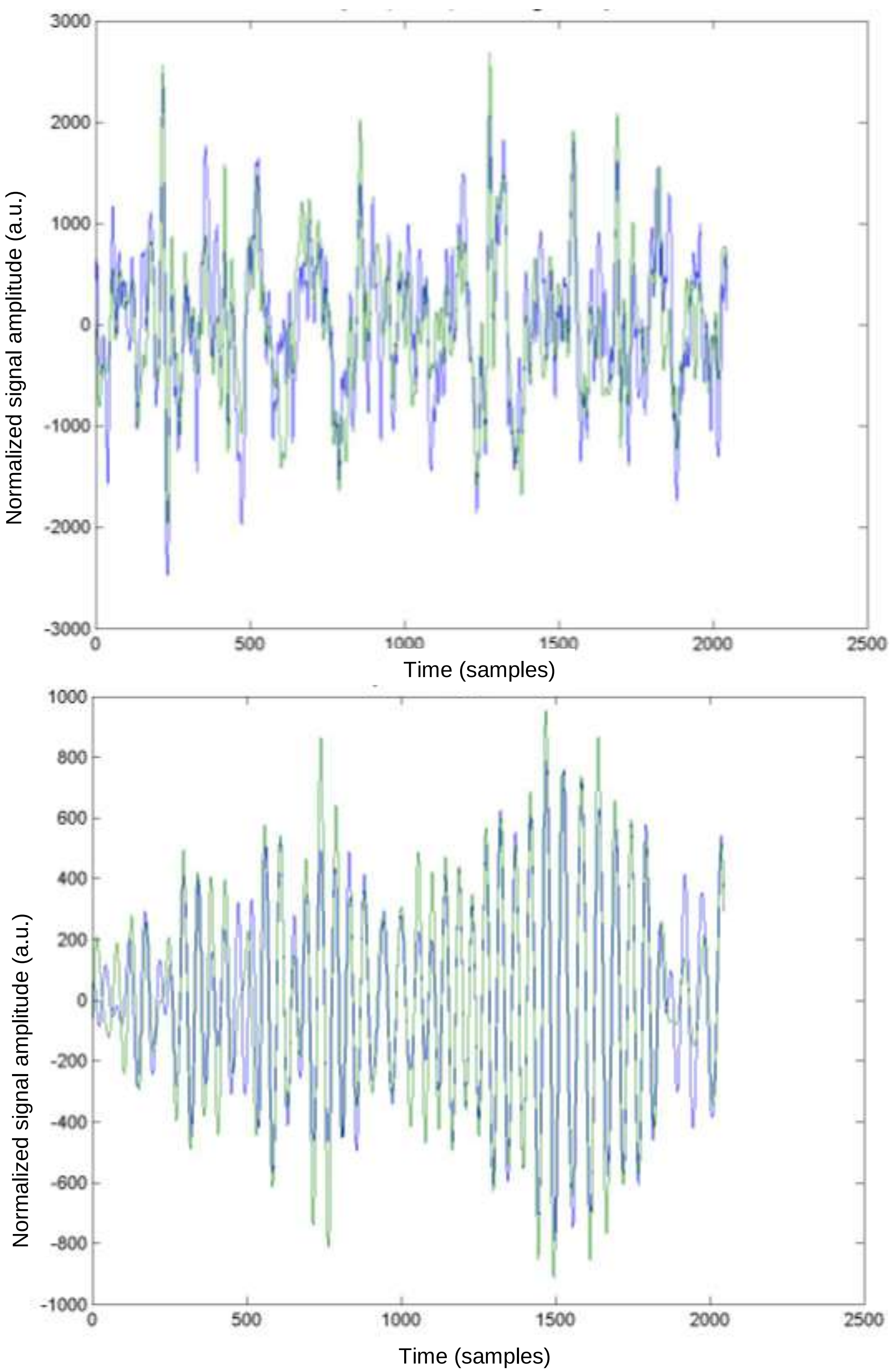


Figure 8. Comparison of the dry (blue line) and wet (green line) electrodes EEG signals, band-pass filtered in the 2-35Hz (top figure) and 8-12Hz (bottom figure).The sampling rate is 512 samples per second. Figures depict 4s recording.

3.3.3. Measuring alpha brain waves with dry and gel electrodes

The comparison of dry and wet electrodes with respect to detecting the power of the alpha rhythm is depicted in Figure 9 to Figure 23. In these figures we try to illustrate whether it is possible to use dry electrode technology to reliably detect brain signals in the alpha frequency range, and whether and to what extent it is more difficult to do that compared to the gel electrodes.

The first figures depicts a graph representing the ratio between the alpha power and the power in 2-35Hz frequency range, measured with dry electrodes and gel (wet) electrodes for each subject (Figure 9, Figure 12, Figure 15, Figure 18, and Figure 21). The comparison is done for three conditions, eyes open, eyes closed without mental task, and eyes closed with mental task. Each condition is repeated three times. The bars represent the standard deviation of the three sessions.

Comparing the ratios for different subjects, we can see that in almost all cases the higher ratio is achieved with wet electrodes. For the first three subjects the differences are small, while for the last two they are quite large. We were not able to explain the reason for this result. However, if we compare the ratio of the alpha power for three different situations measured with dry electrodes on one hand and with wet electrodes on the other we can see that it stays the same. Also the standard deviation is low enough such that we can clearly distinguish the three “mental states”, except for Subject 5. In one of the measurements with eyes open for Subject 3 there was significant artefact contamination for both dry and wet electrodes; therefore we consider that this should not impact the discrimination of the states.

The other two figures depict the power density spectra up to 55Hz (band-pass filtered in the 2-70Hz frequency range) per subject, measured with dry electrodes and wet electrodes respectively. Dry electrodes power density spectra is depicted in Figure 10, Figure 13, Figure 16, Figure 19, and Figure 22, and wet electrodes power density spectra is depicted in Figure 11, Figure 14, Figure 17, Figure 20, and Figure 23.

Comparing the spectra we can clearly see similar power distribution per frequency. In some cases the power in the alpha band is significantly larger than in the rest of the frequency band for the wet electrodes compared to the dry ones. Also, the spectra in the higher frequency band (more than 12Hz) is much “smoother” for the wet electrodes, while the low frequency components (less than 8 Hz) and power line (50Hz) noise are more pronounced for the dry electrodes.

When focusing only on the alpha band we can see that the power distribution has the same shape for the dry as for the wet electrodes. This indicates that EEG signal measured by the dry electrodes is of similar quality to the one measured with the wet ones, as far as alpha power is considered. Based on the analysis we performed we can conclude that we are able to achieve sufficient signal quality to monitor the difference in alpha activity as an indication for the mental activation:

- Difference in processing of external input: eyes open vs. eyes closed state
- Difference in mental relaxation vs. mental activity: eyes closed without mental computation vs. eyes closed with mental computation (alpha de-synchronization)

This also suggests that the dry electrode technology, i.e., dry electrodes, is suitable for measuring the spectral power in the narrow frequency range localized at certain brain regions, such as, e.g., SSVEP response. This is the goal for our further investigation.

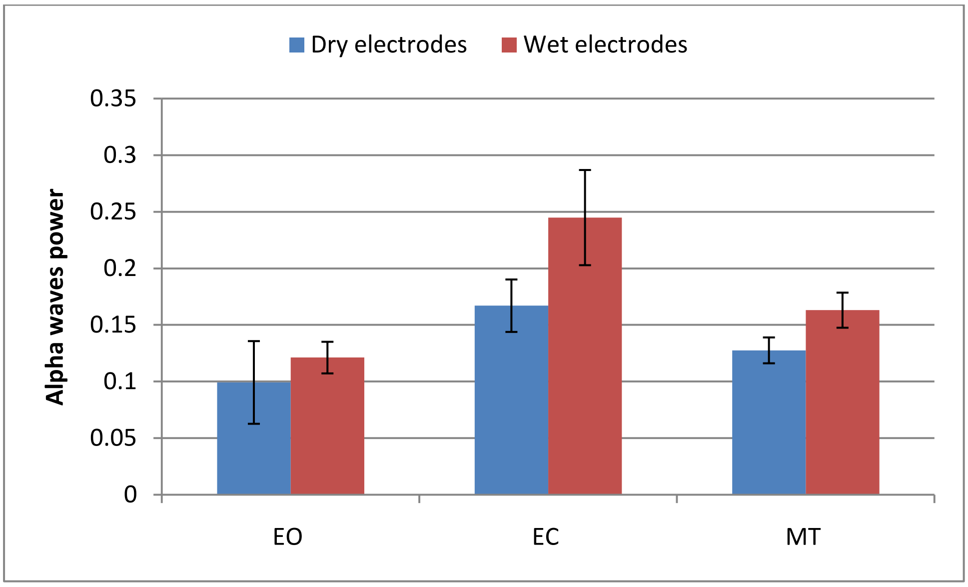


Figure 9. Power in the alpha frequency band (8-12Hz) of Subject 1, measured relative to the power in the 2-35Hz frequency band, using dry and wet electrodes for eyes open (EO), eyes closed without mental task (EC), and eyes closed with mental task (MT).

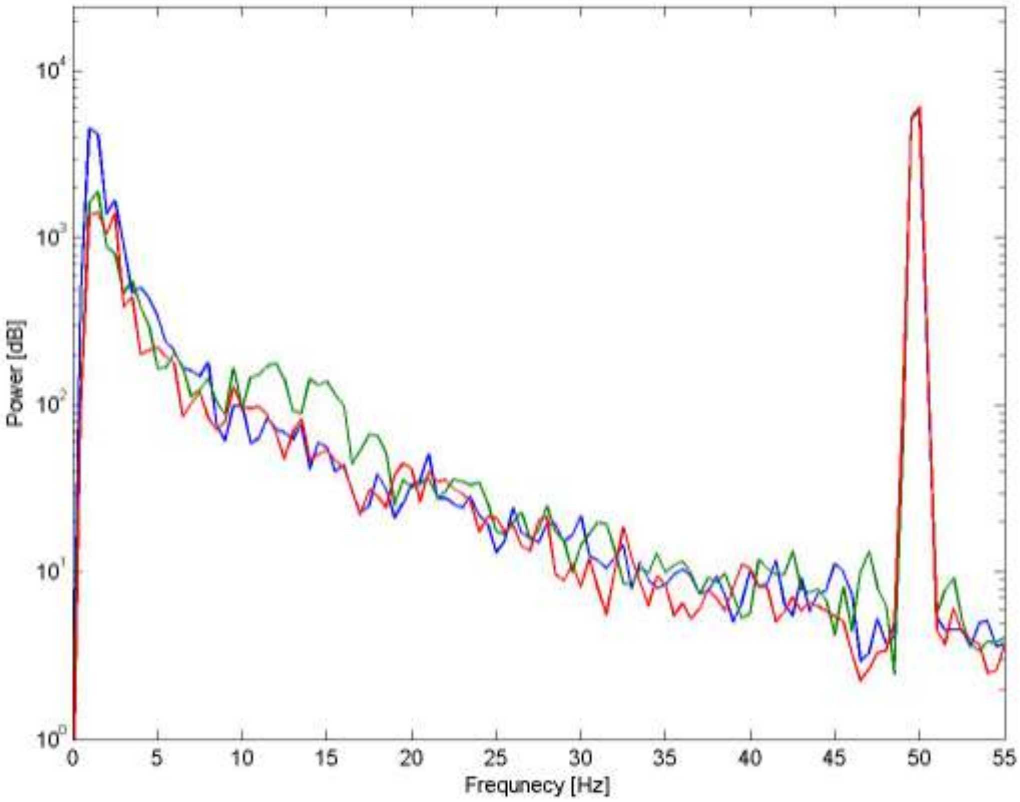


Figure 10. Power density spectra for Subject 1 measured with dry electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

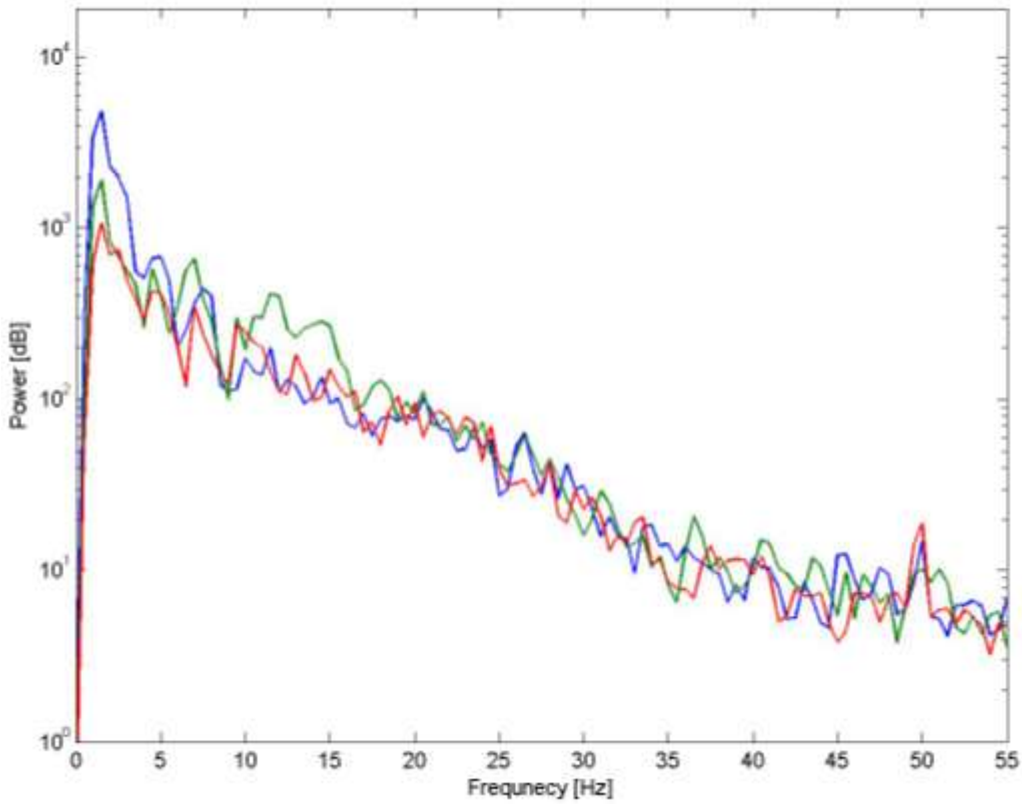


Figure 11. Power density spectra for Subject 1 measured with wet electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

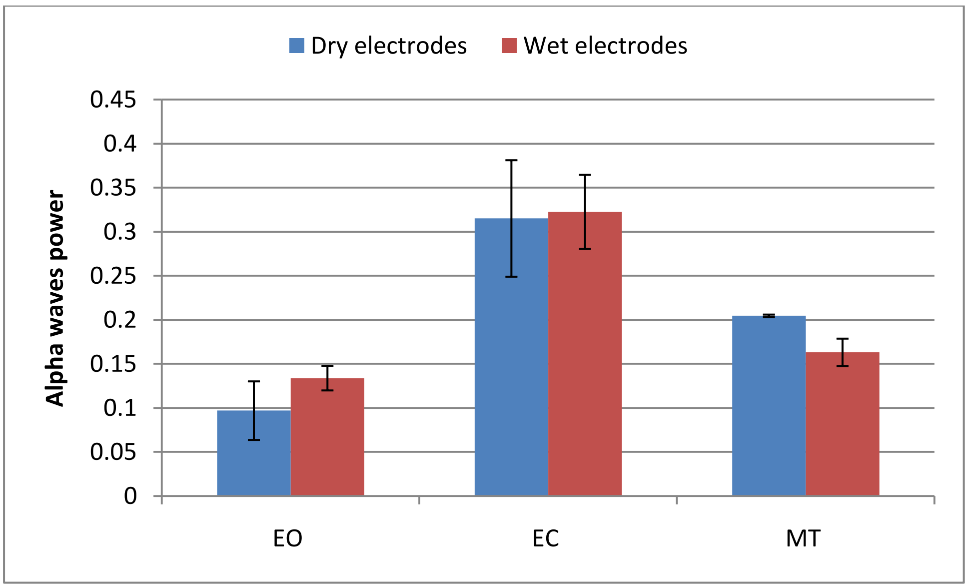


Figure 12. Power in the alpha frequency band (8-12Hz) of Subject 2, measured relative to the power in the 2-35Hz frequency band, using dry and wet electrodes for eyes open (EO), eyes closed without mental task (EC), and eyes closed with mental task (MT).

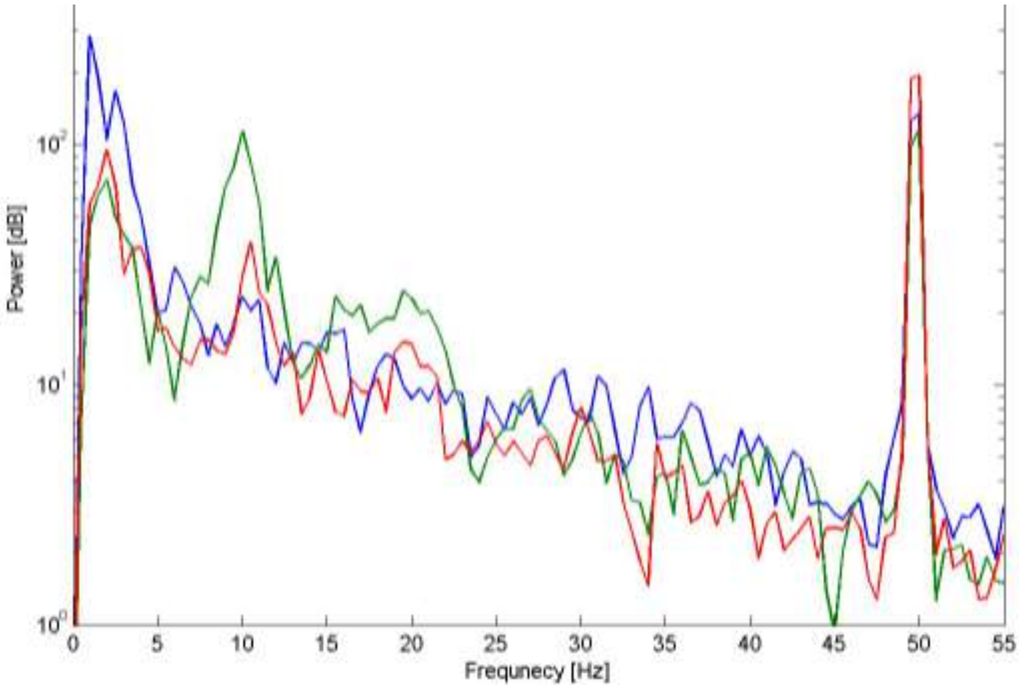


Figure 13. Power density spectra for Subject 2 measured with dry electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

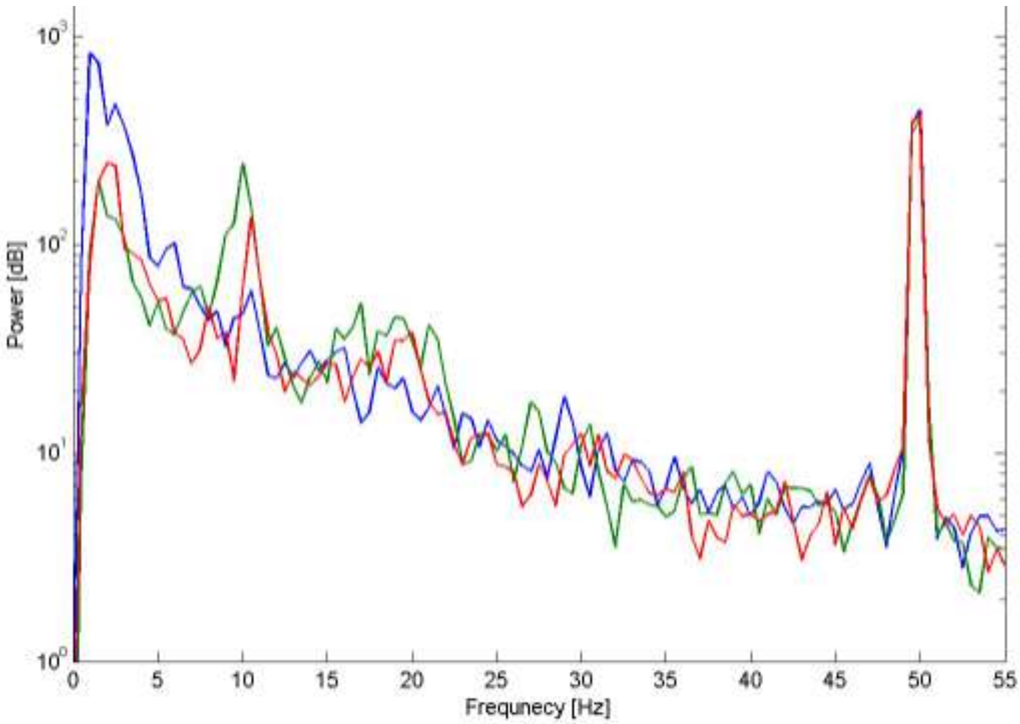


Figure 14. Power density spectra for Subject 2 measured with wet electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

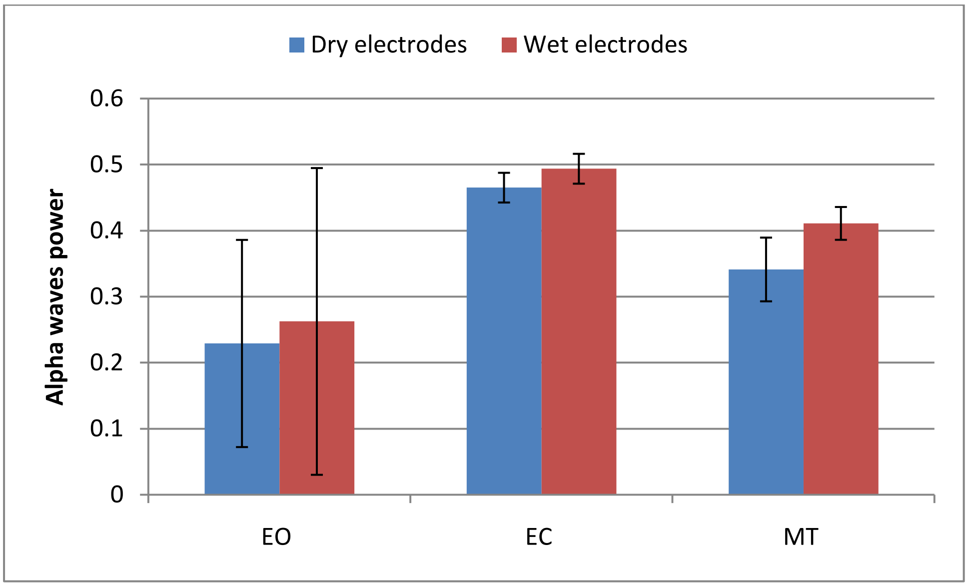


Figure 15. Power in the alpha frequency band (8-12Hz) of Subject 3, measured relative to the power in the 2-35Hz frequency band, using dry and wet electrodes for eyes open (EO), eyes closed without mental task (EC), and eyes closed with mental task (MT).

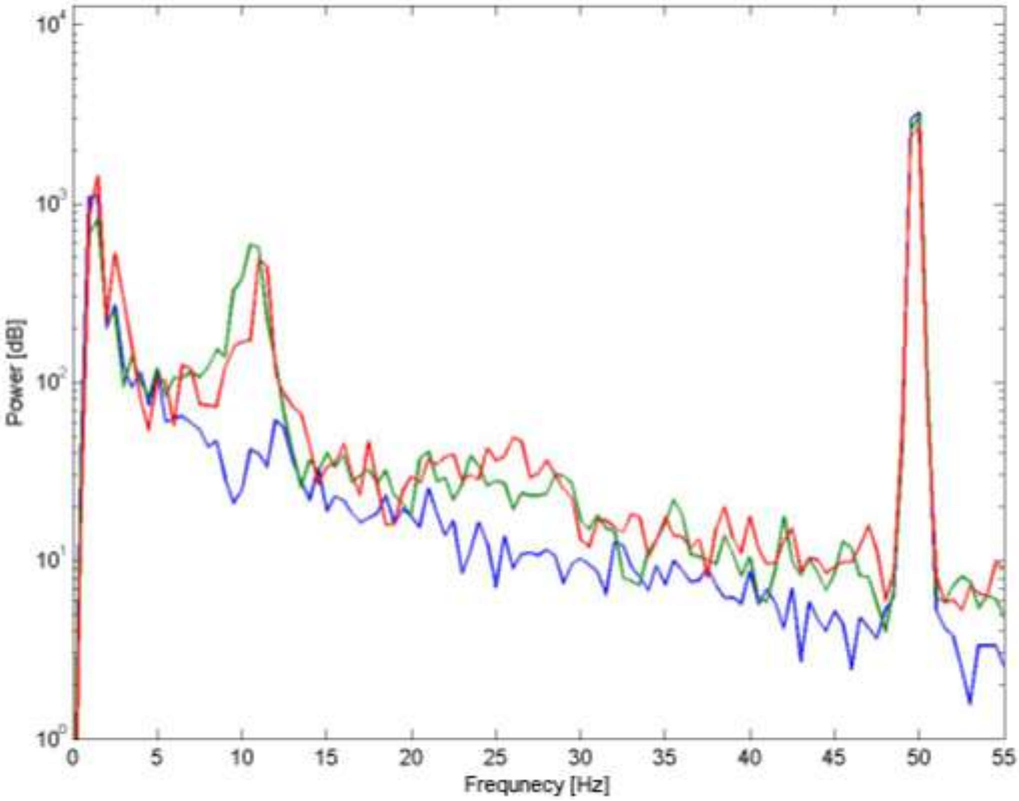


Figure 16. Power density spectra for Subject 3 measured with dry electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

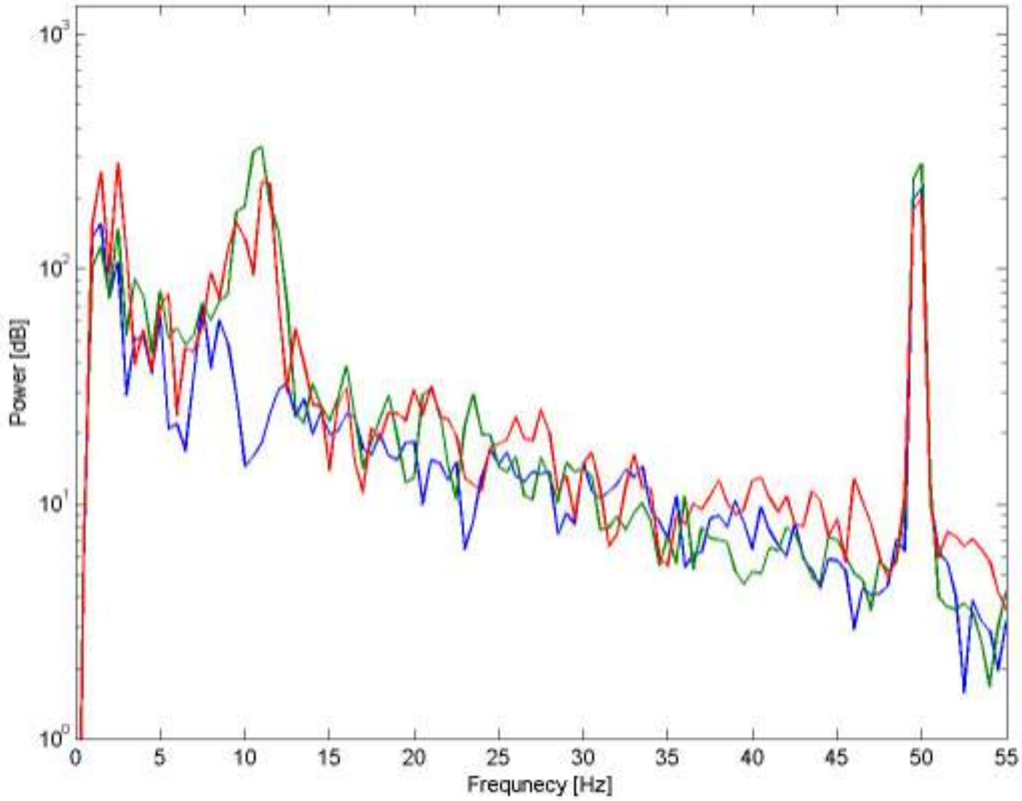


Figure 17. Power density spectra for Subject 3 measured with wet electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

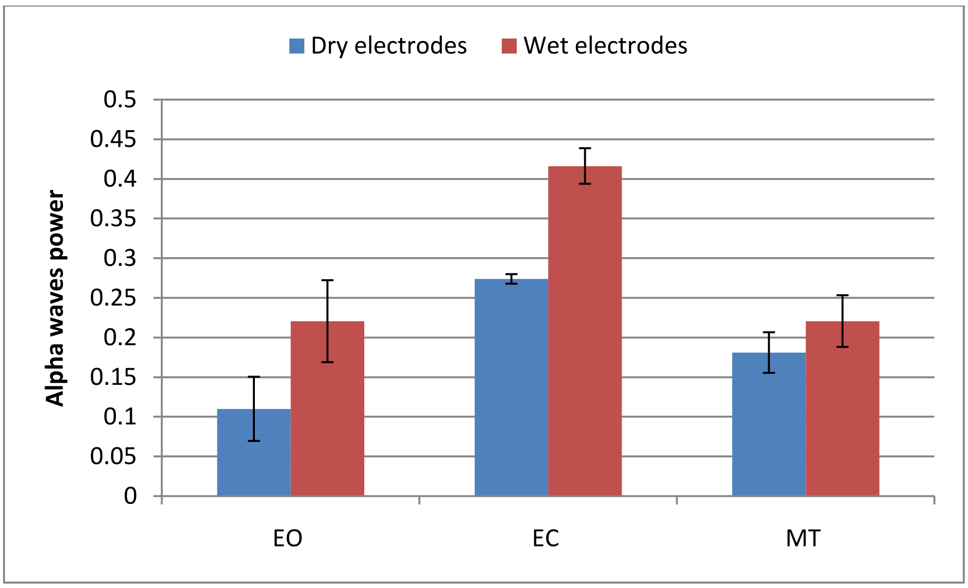


Figure 18. Power in the alpha frequency band (8-12Hz) of Subject 4, measured relative to the power in the 2-35Hz frequency band, using dry and wet electrodes for eyes open (EO), eyes closed without mental task (EC), and eyes closed with mental task (MT).

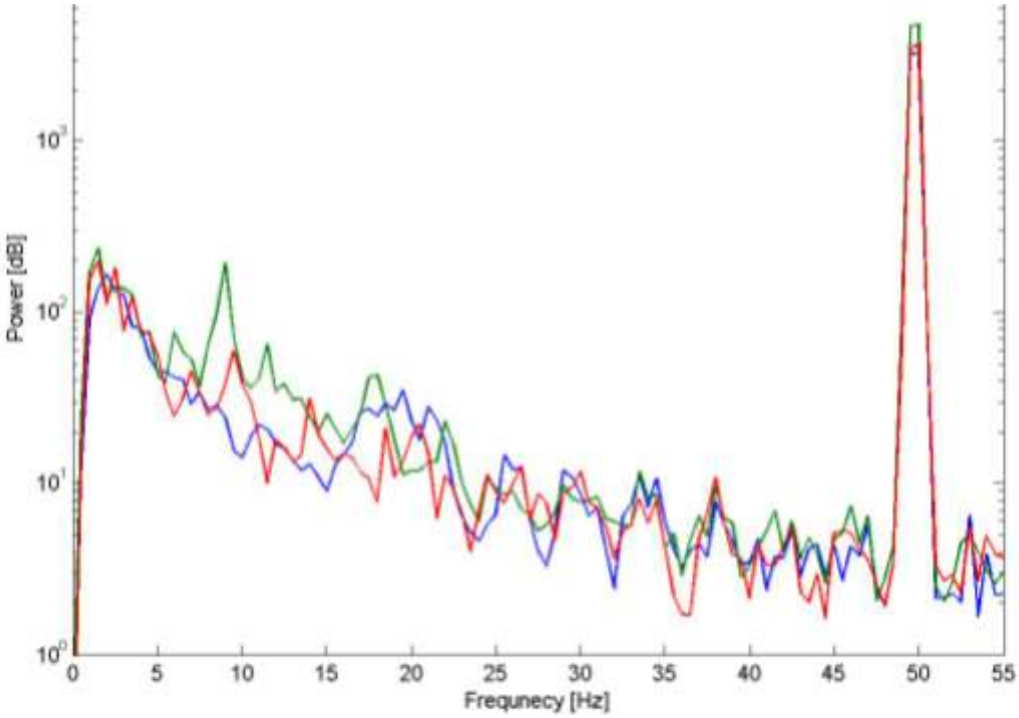


Figure 19. Power density spectra for Subject 4 measured with dry electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

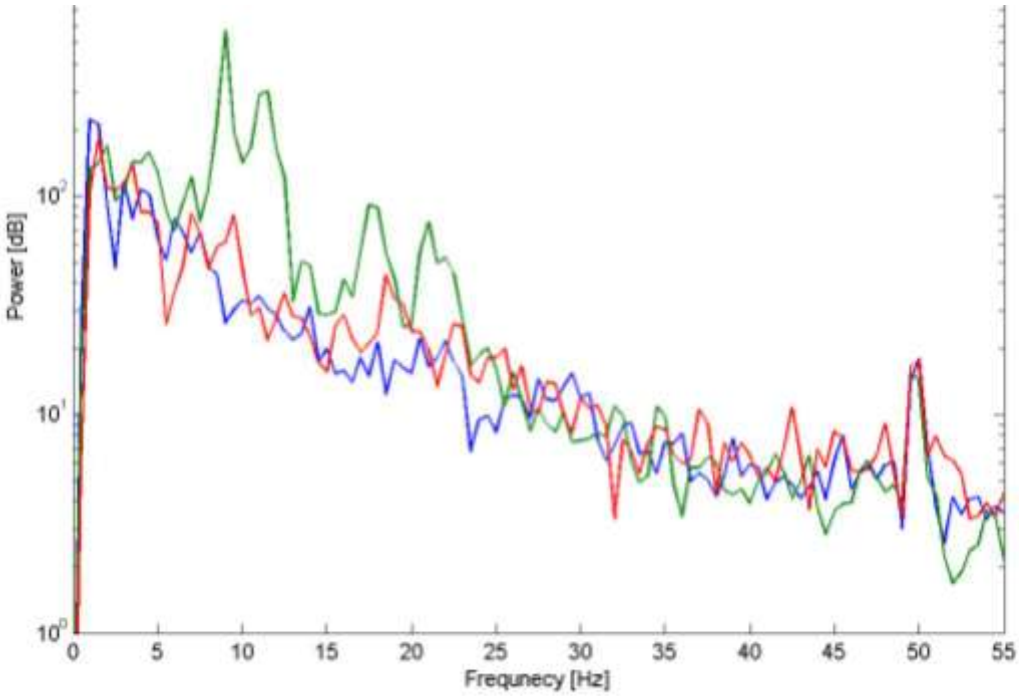


Figure 20. Power density spectra for Subject 4 measured with wet electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

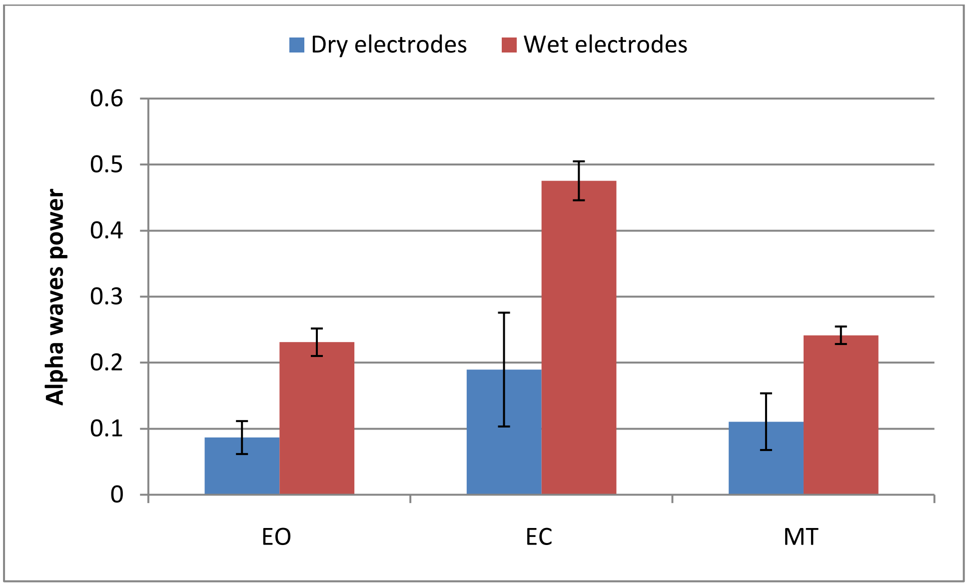


Figure 21. Power in the alpha frequency band (8-12Hz) of Subject 5, measured relative to the power in the 2-35Hz frequency band, using dry and wet electrodes for eyes open (EO), eyes closed without mental task (EC), and eyes closed with mental task (MT).

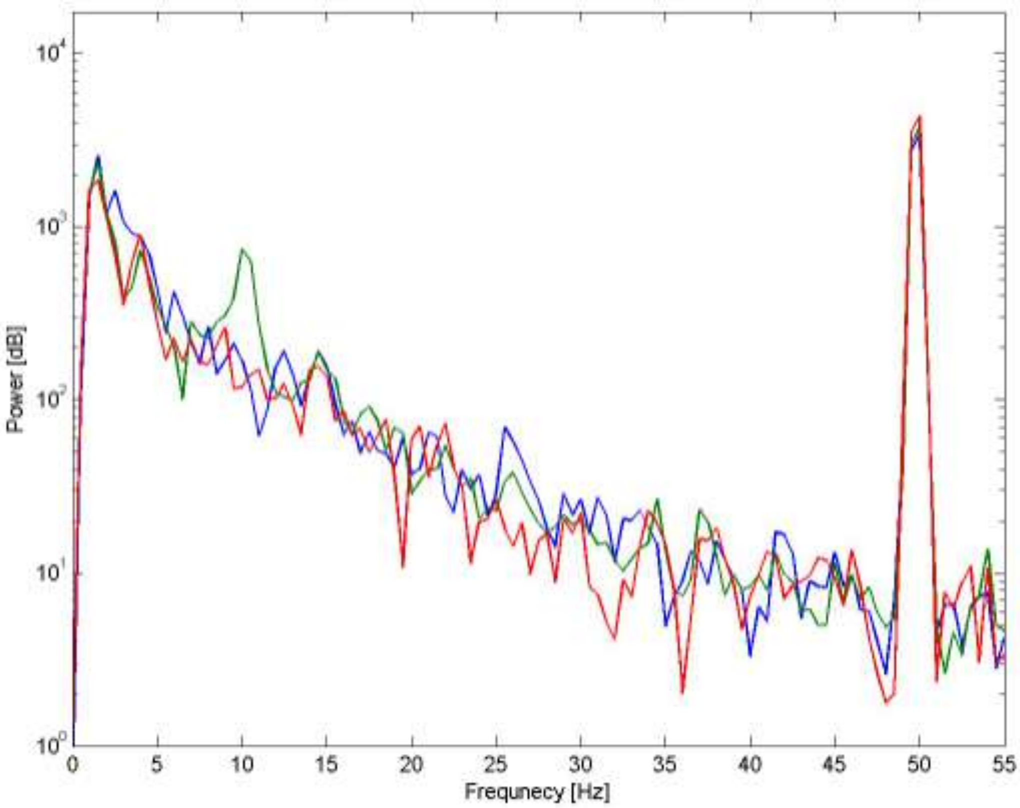


Figure 22. Power density spectra for Subject 5 measured with dry electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

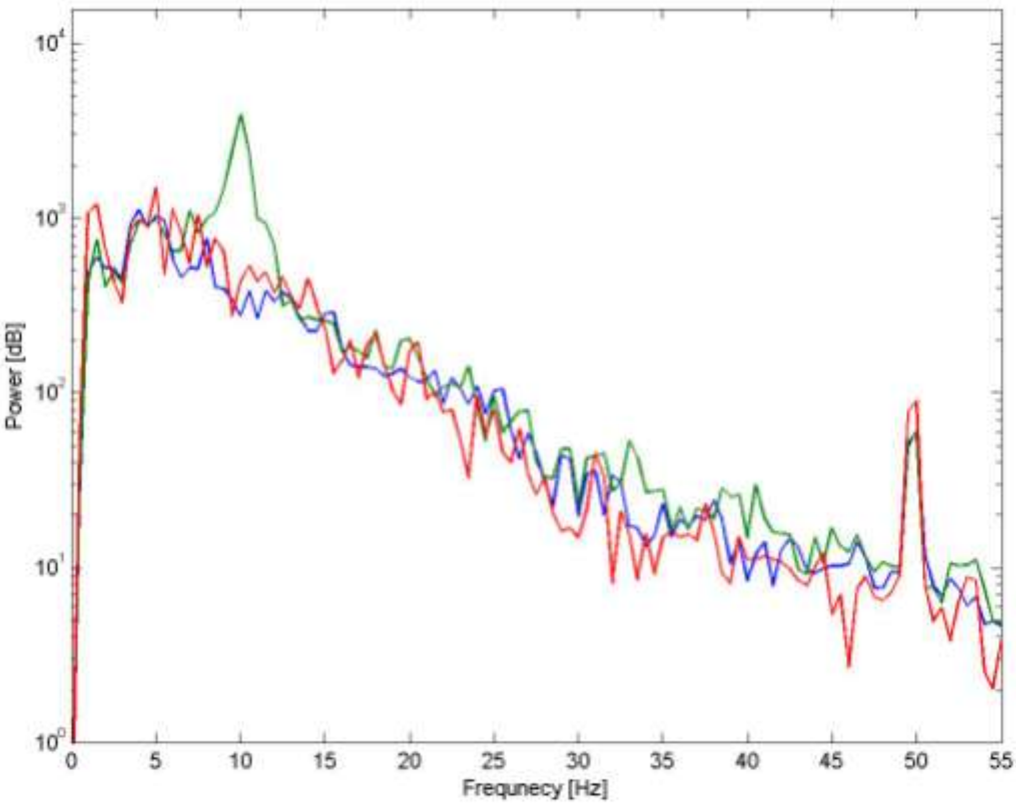


Figure 23. Power density spectra for Subject 5 measured with wet electrodes, band-pass filtered in the 1-70Hz range. The blue line represents eyes open segment, the green line represents segment with eyes closed without mental computation, and the red line represents segment with eyes closed with mental computation.

4. Impedance measurement

This section details our effort in estimating what is the input impedance the amplifier can expect when the setup with dry electrodes with pin structures are used for measuring brain signals. The dry electrode impedance is compared to the typical usage of gel electrodes for the same purpose. As this process is not trivial we first describe the measurement setup and the evaluation protocol we used and then focus on the obtained results.

Skin impedance measurement has been a standard practice for a number of years [13]. However, the impedance is typically measured on the human forearm or other places with few hairs and where contact to skin can be easily established. Typically, results are reported as impedance magnitude and phase when applying different frequency AC voltages or by drawing a Cole-Cole plot (graph showing the relationship between real and imaginary part of the impedance) [14].

A Cole-Cole plot that has a U-shape is often seen in forearm measurements if the range of frequencies is sufficient (e.g., up to kHz ranges). This predictable behaviour led to models that depict the conductive properties of the skin. Up to our knowledge no systematic measurement of head skin conductive properties (including the influence of hair), especially in combination with dry electrodes, has been performed. Consequently, no models exist that can be applied to describe the conductive properties of the skin. That is why we approach the skin impedance measurement on the head with the special attention on measurement setup and the evaluation of the measured results.

4.1. Measurement setup

Skin impedance is measured by the principle of a measurement bridge, as depicted in Figure 24. In the figure Vout represents the applied (AC) voltage, V0 the voltage as measured over a known resistance R0 and V1 the voltage as measured over the unknown impedance Z1. By using Ohm's law and Kirchhoff's circuit laws, we derive Equation 1, which can be used to compute the unknown impedance value Z1.

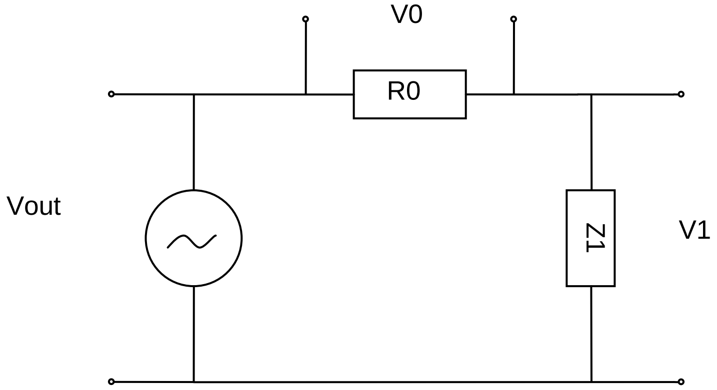


Figure 24. Skin impedance measurement setup.

$$\frac{V1}{Z1} = \frac{V0}{R0} \Rightarrow Z1 = \frac{R0 \times V1}{V0} \qquad (1)$$

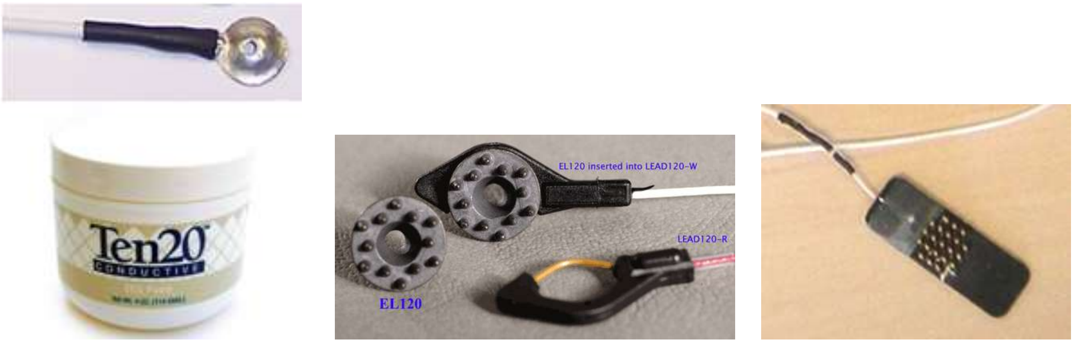
In practice, Equation 1 is only used to compute the magnitude of the complex impedance, by measuring RMS values for the measured voltages, for enhanced SNR. The phase of Z1 is determined by computing the Fourier transform of both V1 and V0. The difference between the angles of these Fourier representations at the frequency of Vout is then the phase of Z1 at this frequency.

The measurement was carried out with a NI USB-6229 Multichannel DAQ board, by National Instruments. The delay between the (multiplexed) inputs of these inputs was taken into account in determining the phase delay. The data acquisition and computations was done using specially developed Matlab tools. Calibration of the setup was done will be done both by using known resistor values for Z1.

4.2. Evaluation protocol

The goal of the evaluation was to estimate what are the typical values of the impedance magnitude and phase when various dry electrodes are positioned on a person’s head and how they compare to the values obtained when using gel electrodes on the forearm and the head. Additionally, subjective perception of participants is evaluated using a simple questionnaire. Here we describe how the designed user test looks like.

The user test lasted for 75 minutes and it consisted of the three main stages: introduction stage, measurement stage, and discussion stage. The introduction stage is intended for preparing the user for the experiment and it lasted for about 10 minutes. The electrodes we used in the experiment are commercially available AgCl electrodes that are used in combination with gel (depicted in Figure 25a), referred to as gel electrodes, commercially available sintered Ag/AgCl electrodes with pin structure (see Figure 25b), and in-house developed gold-plated electrodes in a silicon substrate (see Figure 25c), discussed in previous sections.



a) b) c)

Figure 25. Different electrodes used in the evaluation: a) AgCl electrodes used with gel (gel electrodes); b) dry Ag/AgCl electrodes with pin structure; c) dry gold-plated electrodes with pin structure.

The measurement stage consists of a number of measurements where two gel electrodes are mounted on the user’s forearm at the distance of 10cm followed by mounting three types of electrode pairs on the user head where the distance of the electrodes is approximately 10cm (roughly at positions C3 and C4 according to the 10-20 International system). The setup on user’s head is achieved by attaching the electrodes to the off-the-shelf headphones. The data about the computed resistance (impedance) is recorded for each setup. This stage lasted for 50 minutes. Each recording was done using the output voltage of 1V and the frequency sweep was done in steps of 5Hz in the frequency range from 2 to 45Hz and in steps of 50Hz in the frequency range from 50 to 500Hz.

During the last stage the user provided his remarks and comments on the performed test. This stage lasted for about 5 minutes.

Detailed description of the stages is as follows:

1. Introduction stage (10 minutes)
    a. The user is informed about the purpose and the setup of the experiment (5 minutes)
    b. The consent form is explained and handed to the user for signing (5 minutes)
2. Measurement stage (45 minutes)
    a. Gel electrode measurements on the user's forearm (8 minutes)
        i. Gel electrodes are placed on the user's forearm (2 minutes)
        ii. The first measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
        iii. The second measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
    b. Ag/AgCl prototype headset measurements (20 minutes)
        i. Ag/AgCl prototype headset is mounted on the user's head and left for up to 1 minute to stabilize (2 minutes)
        ii. The first measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
        iii. Ag/AgCl prototype headset is taken off and mounted again on the user's head and left for up to 1 minute to stabilize (2 minutes)
        iv. The second measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
        v. Ag/AgCl prototype headset is taken off and mounted again on the user's head and left for up to 1 minute to stabilize (2 minutes)
        vi. The third measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
        vii. Ag/AgCl prototype headset is left for up to 2 minutes on the user's head (2 minutes)
        viii. The fourth measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
    c. Gold-plated prototype headset measurements (20 minutes)
        i. Gold-plated prototype headset is mounted on the user's head and left for up to 1 minute to stabilize (2 minutes)
        ii. The first measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
        iii. Gold-plated prototype headset is taken off and mounted again on the user's head and left for up to 1 minute to stabilize (2 minutes)
        iv. The second measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
        v. Gold-plated prototype headset is taken off and mounted again on the user's head and left for up to 1 minute to stabilize (2 minutes)
        vi. The third measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
        vii. Gold-plated prototype headset is left for up to 2 minutes on the user's head (2 minutes)
        viii. The fourth measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
    d. Gel electrode measurements on the user's head (9 minutes)
        i. Gel electrodes are placed on the user's head (3 minutes)

ii. The first measurement is performed and the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)
iii. The second measurement is performed where the resistance is computed for the frequencies in the range of 2 to 500Hz (3 minutes)

3. Discussion stage (5 minutes)
   a. The user is given time to fill the questionnaire about the comfort of wearing the prototypes (3 minutes)
   b. The user is asked to give additional comments about the experiment (2 minutes)

The questionnaire given to the user contains the following two questions for each type of the electrodes:

- How would you estimate the level of comfort of the tested electrode prototype?
- Would you wear this prototype during your daily activity?

On the first one the participant has to answer by giving a mark on a scale 1 (uncomfortable) to 10 (comfortable) and on the second one with a simple yes and no. There is also space for additional remarks about the evaluation and the prototypes used in the questionnaire.

4.3. Evaluation results

This section presents the results of evaluating the dry electrode prototypes with five subjects. First we present the typical impedance magnitude and phase values followed by the averaged results across subjects. Then we present what the user's thought about the comfort of the designs and emphasise the main conclusions.

4.3.1. Impedance magnitude and phase responses

Figure 26 displays the impedance magnitude values measured for Subject 4 for all different types of electrodes. For each of the electrode type one measurement is used as a representative. The figure shows that the magnitude values for low frequencies are much higher than for the high frequencies for all electrode types. In most cases the magnitude measured at the 2 and 7Hz is at least twice as high as resistance measured at 500Hz. We can see that the range of impedance magnitude for the frequencies 100-500Hz is below 250kΩ, while it rapidly increases to 1MΩ values at lower frequencies.

Comparing different electrode types we can see that gel electrodes have much smoother transition in magnitude coming from higher to lower frequencies than dry electrodes, where gel electrodes positioned on the head have higher impedance magnitude at higher frequencies. Also, the impedance of gel electrodes is much higher than typically reported in the literature which was mainly due to the fact that we did not prepare the skin before testing the electrodes. Comparing the magnitude of dry electrodes we can see that the values are more-less similar above 50Hz. However, the impedance magnitude values for gold plated electrodes are much higher than the values for the Ag/AgCl electrodes (see Table 4 for comparison).

The phase response of gel electrodes shows smooth transition from low to high frequencies, starting at -10° and saturating at -60° for head mounting and -75° for mounting at the forearm, as depicted in Figure 27. The phase response of dry electrodes is quite different. For Ag/AgCl electrodes the phase drops linearly from -10° to -15° in the frequency range of 25 to 500Hz and slightly drops in the low frequency range (2 to 25Hz). This small drop at the lower frequencies is more pronounced with the gold plated electrodes (see Figure 27) where phase goes from -23° at 100Hz to -43° at 2Hz.

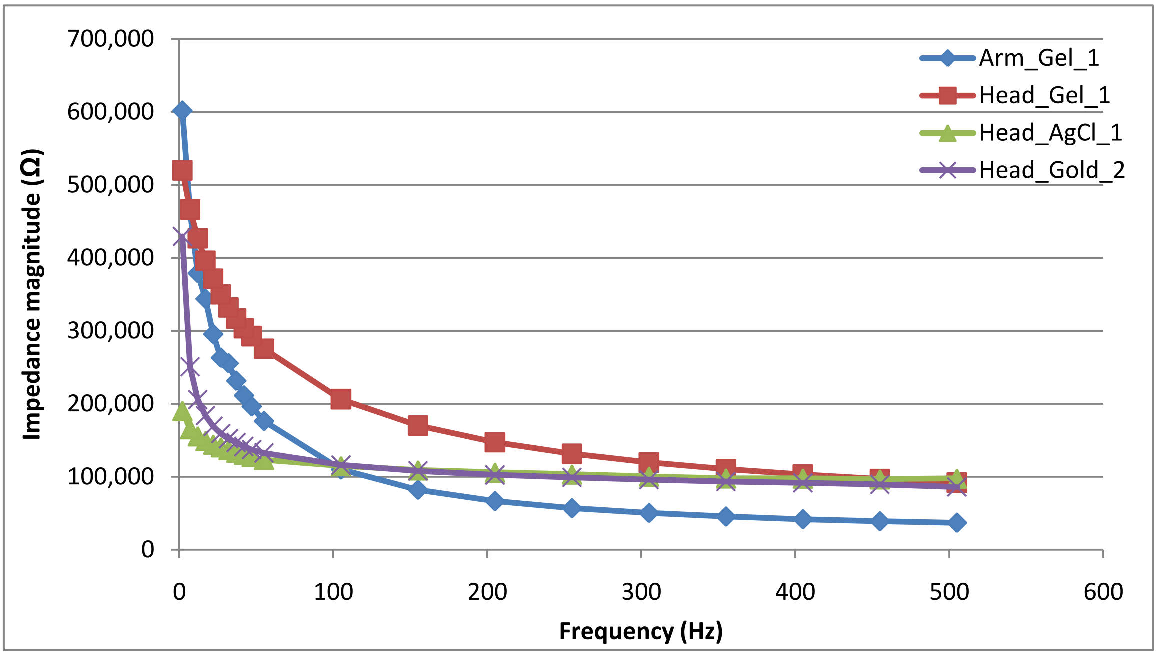


Figure 26. Impedance magnitude values for Subject 4. Gel electrodes positioned on the forearm and on the head, and Ag/AgCl and gold plated electrodes positioned on the head are displayed. The frequencies used in evaluation range from 2 to 500Hz.

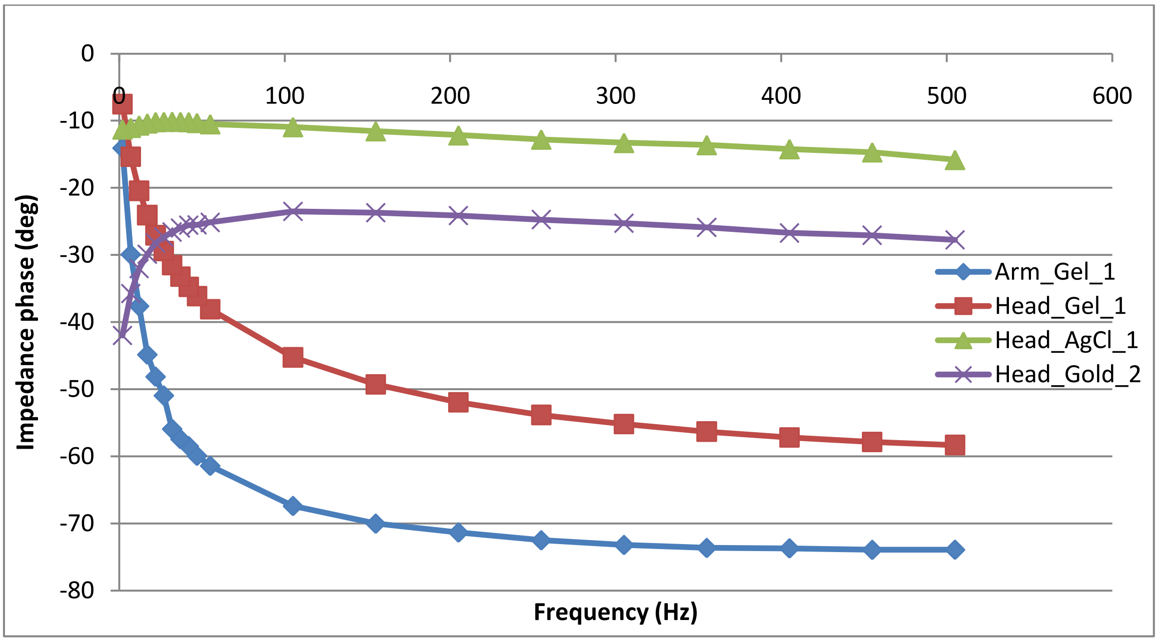


Figure 27. Phase response for Subject 4. Gel electrodes positioned on the forearm and on the head, and Ag/AgCl and gold plated electrodes positioned on the head are displayed. The frequencies used in evaluation range from 2 to 500Hz.

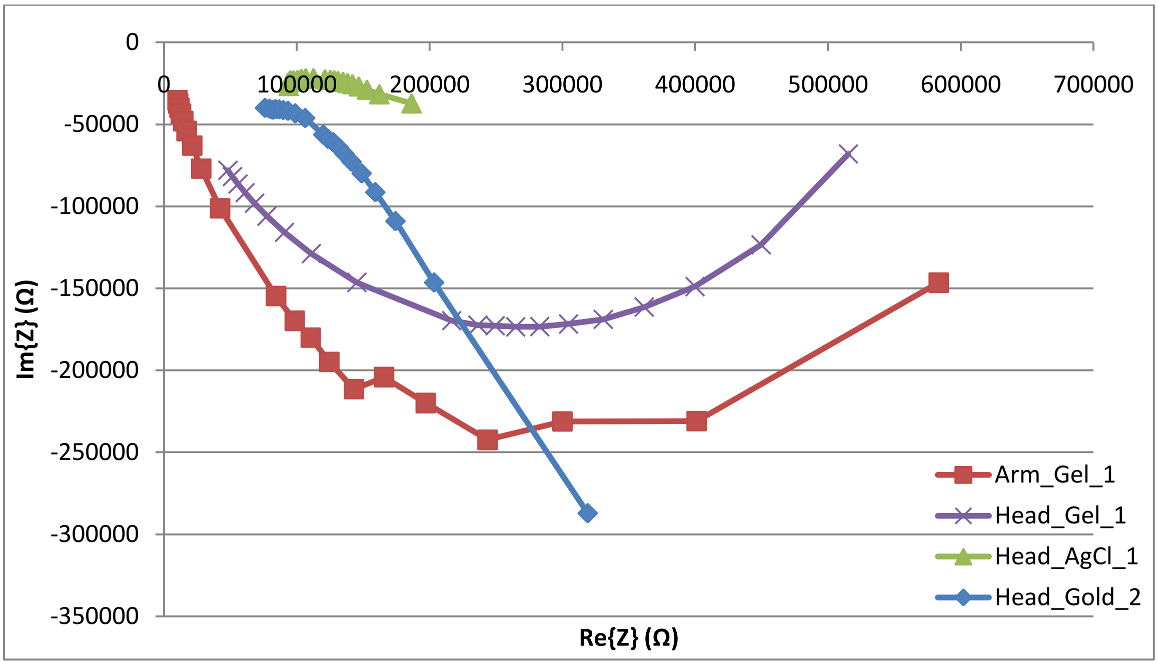


Figure 28. Cole-Cole plot for Subject 4. Gel electrodes positioned on the forearm and on the head, and Ag/AgCl and gold plated electrodes positioned on the head are displayed. The frequencies used in evaluation range from 2 to 500Hz.

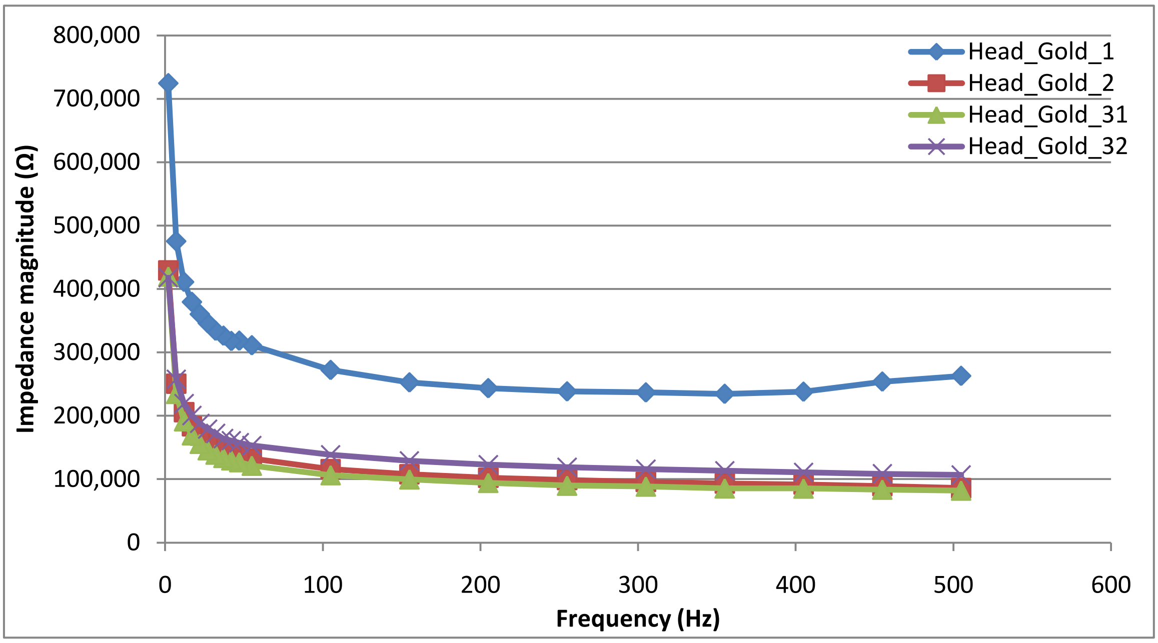


Figure 29. Resistance values for gold plated electrodes positioned on the head of four successive recording of Subject 4 are displayed. The frequencies used in evaluation range from 2 to 500Hz.

Cole-Cole plots for Subject 4 for different electrodes are shown in Figure 28. We can observe that the gel electrodes have the expected U-shape of the curves. However, the Cole-Cole plots for Ag/AgCl and gold-plated electrodes are quite irregular. It is not clear whether using larger range of frequencies (up to 100kHz) will lead to the expected U-shape, or the properties of the skin-hair surface on the head are quite different from the properties of skin on the other areas, e.g., forearm. In other words, the results suggest that the conductance tissue models used for modelling forearm with gel electrodes might not be suitable for modelling the contact interface with dry electrodes at the head. To design a model for skin-dry electrode conductive properties, following this line of reasoning, we have to perform further evaluation of the electrode-skin contact properties on the head.

Looking at the intra-subject variability we can see that in most cases the impedance magnitude values match each other for the same frequency quite closely, except for some of the measurements where the magnitude is significantly higher (first measurement with gold-plated electrodes of Subject 4), as depicted in Figure 29. Our speculation is that not all pins get in contact with the skin on the head, due to either the hair that can come in between or due to the inflexibility of the structure that supports the pins. The same effect can be noticed with the Ag/AgCl electrodes but it is less pronounced than for the gold plated ones (see Table 4). The most probable reason is that the pins in the Ag/AgCl dry electrode prototype are quite sharp and they have a higher chance of getting in contact with the skin.

In most of the cases the phase response is stable, especially in the low frequency range. Small variations can be seen in the slopes for higher frequencies. This is illustrated in Figure 30, where phase response for Subject 4 is depicted.

The repeatability of the results is quite good when Cole-Cole plots are considered. For example, the last three measurements plots with similar shape and data values for the gold-plated electrode measurements of Subject 4, as depicted in Figure 31. The first measurement gives different data points on the plot, which can be explained by different resistance values shown in Figure 29, but still retains similar shape as the other three measurements. The Ag/AgCl electrodes, although having slightly different shape of Cole-Cole plots than the gold-plated ones, have similar shapes across subjects and measurements.

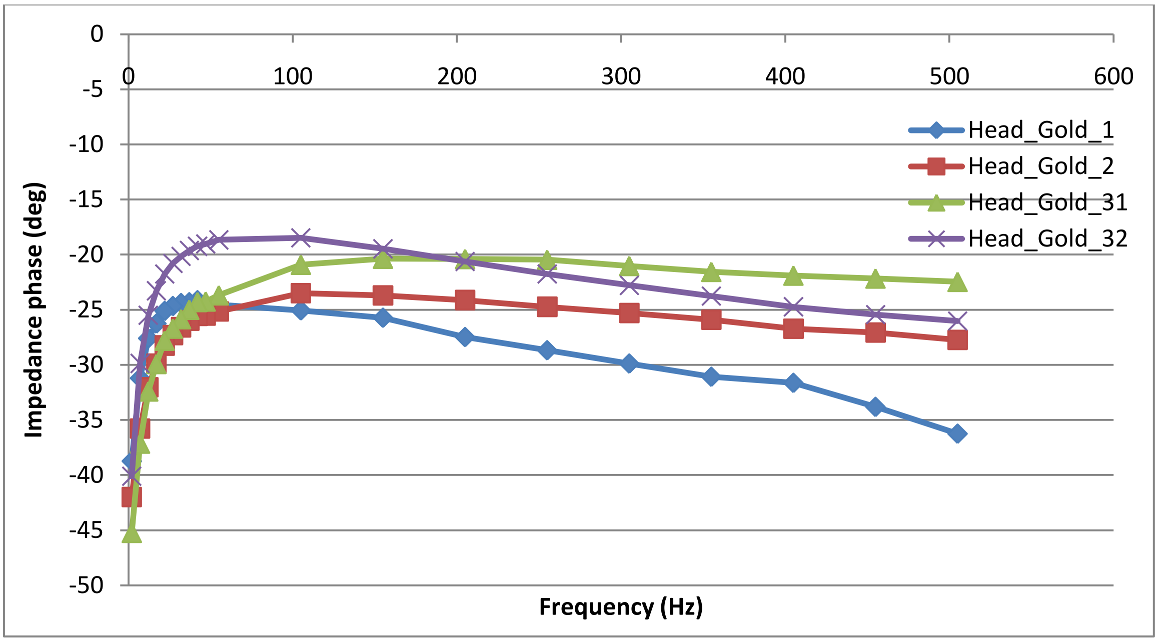


Figure 30. Phase response for gold plated electrodes positioned on the head for four successive recording of Subject 4 are displayed. The frequencies used in evaluation range from 2 to 500Hz.

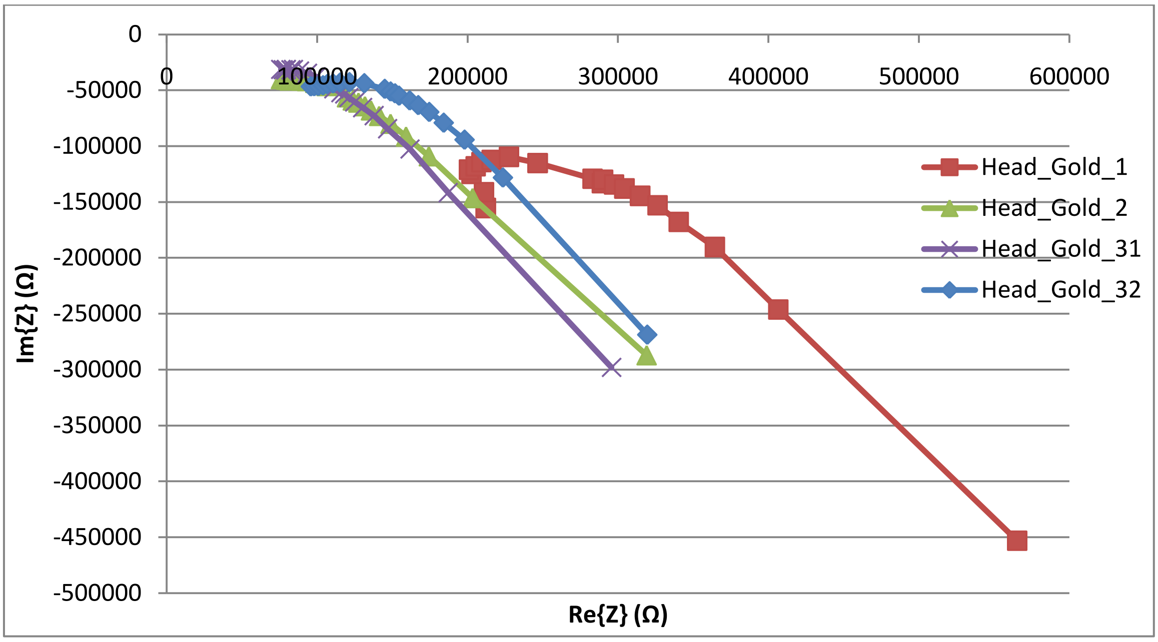


Figure 31. Cole-Cole plot for gold plated electrodes positioned on the head for four successive recording of subject 4 are displayed. The frequencies used in evaluation range from 2 to 500Hz.

4.3.2. Comparison of different electrode impedance magnitude

The frequency area of interest in our case lies in the alpha band, i.e., 8-12Hz. Therefore, we had a closer look at the impedances in this range. Since we measured the impedance in steps of 5Hz, we report the 7Hz and 12Hz results. As shown in Table 4, the lowest impedance magnitude is achieved on average with Ag/AgCl dry electrodes, followed by gel electrodes and then the gold electrodes. On the other hand we can see much larger variation in the measured magnitude for dry electrodes, especially for the gold-plated ones (see Standard deviation column in the table). This is due to the variation of resistance values obtained across subjects, but also due to the intra-subject variability described above.

Table 4. Impedance magnitude values for gel electrodes positioned at the user's forearm and head, and Ag/AgCl and gold-plated electrodes placed on the users head, averaged over all users and all trials at 7Hz and 12Hz.

Impedance magnitude	Data points	7Hz		12Hz	
		Mean (kΩ)	Standard deviation	Mean (kΩ)	Standard deviation
Gel electrodes on the arm	10	560	127	427	113
Gel electrodes on the head	10	402	138	368	122
Ag/AgCl dry electrodes on the head	20	354	312	338	300
Gold dry electrodes on the head	20	638	1049	554	830

4.3.3. The comfort of electrode setup

The evaluation of the electrodes also included the evaluation of the user comfort level while wearing the (prototypes with) electrodes. This is intended to probe how the users perceive the comfort level of the designs. Here we did not use the flexible pin structure but firm pins which are less comfortable. Users marked Ag/AgCl, gold-plated, and gel prototypes mounted on their head in the scale from 1 to 10, where 1 denotes highly uncomfortable and 10 highly comfortable level.

The results of the questionnaire are shown in Table 5. Clearly, all prototypes are perceived as uncomfortable, with the gold-plated electrodes considered as the least comfortable and gel electrodes as most comfortable ones. Additionally none of the users express willingness to use these types of electrodes in everyday life. Further investigation on how to enhance the comfort level of the prototypes, besides using flexible pin structure electrodes, is a desired direction for further research.

Table 5. Assessment of comfort level of Ag/AgCl, gold-plated, and gel prototypes on a 1 (highly uncomfortable) to 10 (highly comfortable) scale.

Subject	Ag/AgCl	Gold	Gel
Subject 1	3	4	7
Subject 2	1	2	1
Subject 3	5	3	8
Subject 4	4	4	1
Subject 5	8	6	9
Average	4.2	3.8	5.2
Standard deviation	2.6	1.5	3.9

4.3.4. Summary of dry electrode impedance measurement

The results of the impedance measurement are summarized here. We stress that during the evaluation we did not address the issue of pressure that each of the electrodes puts on the person's head which is a necessary component for comparing different electrode designs. Also, comfort of the headsets (while wearing it during a longer period of time) was not one of the requirements in the design. Therefore, we see the obtained results useful for estimating the range of impedance magnitude and phase responses we can expect when dry electrode technology is used.

Additional experiments are necessary to compare the electrode material, pressure applied, electrode surface size, electrode surface structure, etc. We plan to address some of these aspects in the follow-up studies.

The following major conclusions can be drawn from the presented evaluation of dry electrode impedance:

1. The expected range of impedance magnitude values for dry electrodes is from 2MΩ for lower frequencies, which are the frequencies of interest in our case, to 100kΩ for higher frequencies.

2. The Ag/AgCl electrode design gives more stable performance for lower frequencies (up to 25Hz) than gold-plated electrode prototype, in terms of less variability of impedance magnitude and phase. This could be due to the material, pin design, pressure, etc.
3. Dry electrodes have unusual phase response, which results in the unexpected shape of the Cole-Cole plots. This could be due to the different properties of the electrode-skin contact and might require re-definition of the typical electrode-skin model designed for forearm.
4. Right positioning of electrodes on the head, i.e., achieving optimal contact between the electrodes and the skin on the head might have greater impact than the electrode material properties and small pressure deviations. A mean of giving feedback to the user on whether he positioned the electrodes properly is beneficial.
5. The shape of the pins and the pressure applied can have significant impact on the resistance values.
6. Inter-personal differences of skin properties on the head result in significant differences in the measured impedance. Potentially skin types might exist that have better properties when used in combination with electrodes of certain type.
7. The comfort level is an important aspect that needs to be addressed when developing dry electrode prototypes. More comfort in essence means less pressure and higher impedance, but this can be compensated with clever electrode surface as well as electrode positioning design within the headset (which is partially addressed in the second dry electrode prototypes we evaluated in Section 3).

5. Conclusions

The developed dry electrodes seem promising for measuring electrical brain activity in a convenient way. The essential characteristics of these electrodes are:

- An array of metal pins embedded in conductive material to increase user comfort and to deliver a better contact with the scalp (lower contact impedance)
- Rounded pin-ends to give hair the possibility to 'roll' away

We have shown that the signal quality of dry electrodes is sufficient to measure alpha brain rhythm, which is confirmed with medically certified amplifier. To validate the design we performed a number of user tests using the newly designed electrodes integrated into the headset. We achieved sufficient signal-to-noise ratios, good enough for measuring a person's brain wave activity in the alpha frequency band. In particular we showed that:

- Difference in eyes open vs. eyes closed alpha activity can be measured
- Difference in relaxed state vs. mentally active state, i.e., attenuation in the alpha frequency band (alpha de-synchronization), can be measured.

Furthermore, to identify the main requirements for further improvement of the signal-to-noise ratio and robustness of the prototype we investigated the typical impedance values for the skin-dry electrode contact during a frequency sweep (2 – 500Hz) of low voltage stimulation. The range of impedance magnitude was from few hundred kΩ to few MΩ for dry electrodes. We also discovered that typical skin electrode electrical contact properties measured on the forearm cannot be replicated at the human head, pointing to further research needed in this area.

Along with the impedance measurement we evaluate the comfort level of the electrodes. The evaluation showed that the user comfort can be impaired by the dry electrodes and that special attention has to be given to the setup of the electrodes in a headset to increase comfort and reduce obtrusiveness.

The following directions for further developments are envisioned:

- Optimization of the dry electrode design: We plan to address electrode material (keeping it "bio-approved" as in the current setup and striving for the low electrode-skin impedance), number of pins, design of soft reference electrodes, and evaluation if the incorporation of dry version of the ground electrode is possible.
- Optimization of the amplifier front-end: The amplifier front-end has to cope with variation in input impedance while existing amplifier technology needs to be adapted for usage with developed dry electrodes.

Our further evaluation would focus on characterizing the EEG signal obtained with dry electrodes in terms of handling noise and DC offsets. We also aim to compare the signal quality of dry electrodes to the one obtained with water (described in the deliverable D2.3) and gel electrodes when applied to one of the BCI paradigms, e.g., SSVEP. Such evaluation would provide evidence on the degree of our achievements in developing water and dry electrode sensors, and their maturity for usage in BCI applications.

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