Internship Report - MSc Mod4NeuCog (M2)

P300 Speller: Participation to a data acquisition campaign with ALS patients

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1 - Introduction

Amyotrophic Lateral Sclerosis is progressive neurodegenerative disease that affects mostly older people. It can be diagnostic when an individual shows lower and upper motor neuron degeneration and, in just a few years, it may lead to a severe condition of muscle weakness. It can affect limb function (motor movements of arms and legs), thoracic function (difficulty to breath) and bulbar function (mouth motor movements limitations - speech, swallowing) [1]. For some patients, this disease means losing the ability to communicate orally and by writing.

For these patients, a possible solution that has already been scientifically explored so that they can communicate again is to use the Brain Computer Interface (BCI) [2-4]. BCI is a technique that translates electric signals from the brain into commands for some device [5] and can be used to perform text typing tasks, such as the P300 Speller (a BCI system that uses P300 waves to allow the patient to control a virtual keyboard displayed on a computer screen) [6].

The P300 wave is an Event-Related Potential [7], so it is possible to identify variations in the pattern of this wave after the presentation of some stimuli, recognizing peaks of neuron action potentials around 300 milliseconds after this stimulus [8]. It can be observed by displaying a keyboard on a screen and flashing lights over the letters. The idea is that if an individual is targeting a specific letter and a light flashes over that letter, it will act as a stimulus that will activate neurons. By suggesting someone to target specific letters and comparing the P300 waves of when the targeted letter was flashed and when it was not, it is possible to model this brain activation [Figure 1]; and then use this model to predict the letter the individual is looking at by just knowing the pattern of the flashes.

A common way to acquire the brain activity data needed to use BCI is with EEG (Electroencephalography), a non-invasive brain data acquisition system that measures electrical potentials of brain activity by using electrodes placed in a cap and an amplifier [9]. While the cap may have different numbers of electrodes and positions, the amplifier is used to amplify the signals captured by the electrodes into some big enough signal that can be displayed.

In 2017, a partnership between the Inria Athena project team and the Nice Pasteur Hospital demonstrated the usability of the P300 speller by disabled patients with ALS [2]. They used a wet electrodes EEG system to allow individuals with ALS to communicate with their environment by typing sentences using a P300 Speller application in real-time and obtained 100% of effectiveness, where all the 20 patients were able to control the system. On the other hand, they pointed to a number of technical and practical issues on working with wet EEG electrodes systems in daily use.

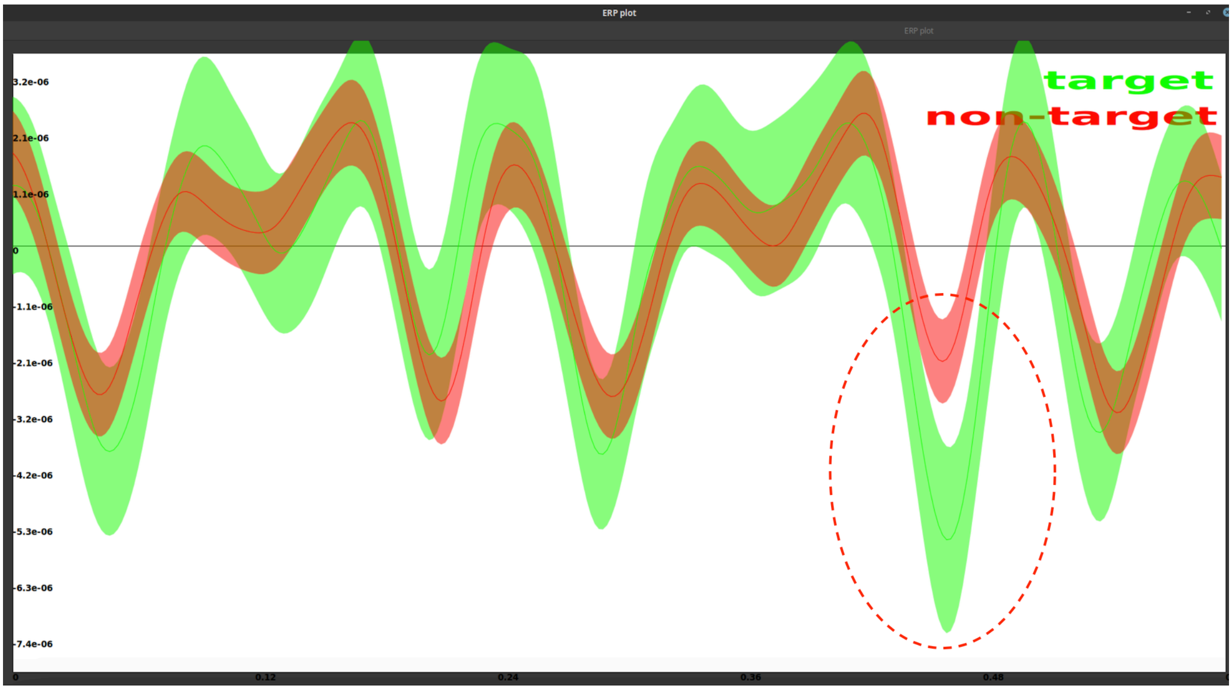

Figure 1 - P300 Wave target x non-target letter. Illustration of the separation of the P300 wave respective to target and non-target evoked responses.

Since the discovery of electroencephalography (EEG) in 1929 [10], the wet electrodes EEG system is the most used when working with EEG. It is well known and trusted by the scientific community, but not very practical to set up. It is necessary to moisten each electrode in the cap with gel before the usage, implying an amount of time to prepare the individual who is using the system and some training on the part of the person configuring the system. More than that, it is also necessary to clean the equipment and the head of the individual who wore the cap after every usage, which further increases the practical issues of using wet electrodes EEG systems regularly.

A new type of dry electrode EEG systems technology is on the rise and could be a possible solution to setup time problems. While some research demonstrates that online performance is significantly poorer than for wet electrodes for users with and without disabilities [11], others claim that they were able to detect as good as wet electrodes EEG system signals measurement with dry electrodes technology [12].

The main problem surrounding the adoption of dry electrodes EEG systems is the high impedance level. Impedance can be simplified as the equivalent of the resistance for a current circuit, which means that the higher the impedance level, the worse the quality of the brain activity signal collection, resulting in an underperforming BCI. The most problematic type of impedance is the impedance between the skin and the electrode; this is why EEG systems rely on the use of gel. The gel works as a good bridge for the current to pass through the scalp to the electrode. The good news is that although the high impedance of dry electrodes is still a challenge, it can be compensated by high input impedance amplifiers [13].

With those specific amplifiers, studies are being made to test the quality of the signal obtained using dry electrodes EEG systems, even when impedance levels are high. It has been shown that it is possible to evaluate dry electrode systems through a comparison to standard wet electrode systems using metrics as: Signal correlations, Signal-to-Noise Ratio (SNR) and P300 Component Analysis metrics [14]. More than that, it is important to note that outliers in signal quality might be related to a bad contact of the electrodes to the skin and not to the high skin-electrode contact impedance magnitude [15].

In the past few years, scientists pointed out the great level of quality achieved by dry electrodes EEG systems solutions, since it was able to guarantee the same quality levels of wet electrodes systems, allowing at the same time to significantly reduce times of montage and increase users comfort [16]. It was also shown that the performance correlated well between the two systems for not only various metrics [Figure 2], but for single trial classification results as well [17].

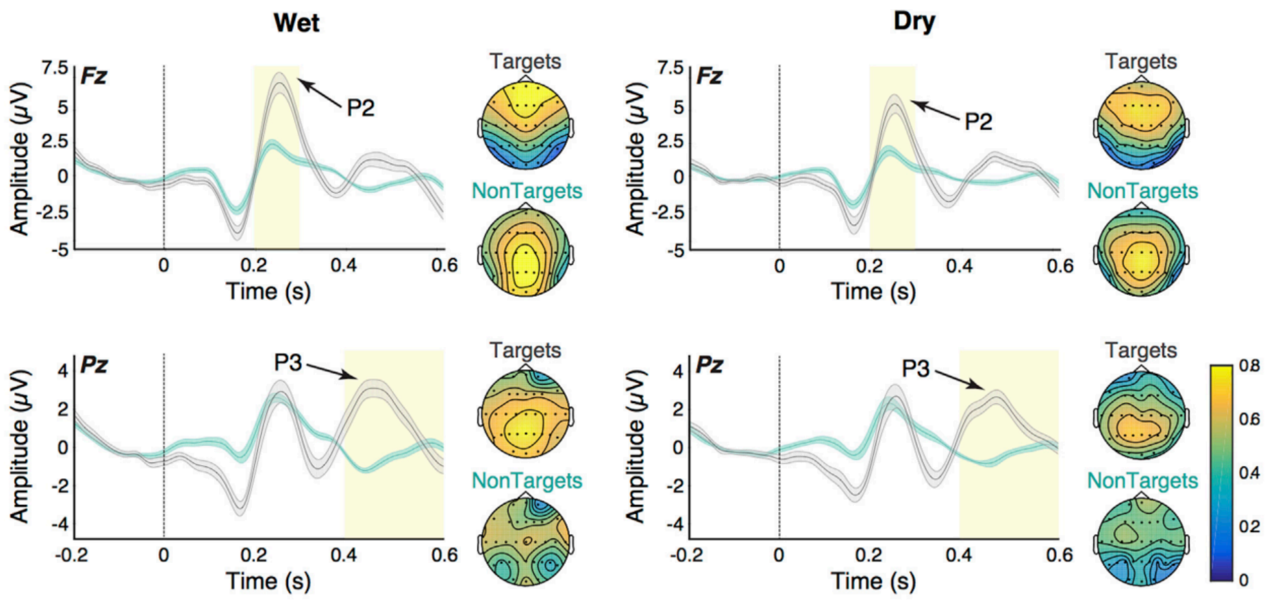

Figure 2 - P300 waves comparison between wet and dry electrodes EEG systems (Kam et al, 2019) [17]. P300 waves acquired using dry electrodes EEG systems might have a lower amplitude or a less well-defined shape when compared to wet electrodes systems ones, but it is well correlated.

Given the advances in dry electrode EEG systems technology, interest arose in re-performing the study carried out in [2] by the Inria Athena project team in partnership with the Nice Pasteur Hospital. The question now is whether it is possible to achieve results levels similar to those of the previous study but using dry electrode EEG systems, allowing individuals with ALS to communicate with their environment by typing sentences using a P300 Speller application in real-time reducing the technical and practical issues on working with wet EEG electrodes systems regularly.

1.1 - Internship activities

As an intern on the Inria Sophia Antipolis Athena project team, I first had to understand how to work with the P300 Speller application with the well-defined wet electrode EEG system solution. In addition to the office work on this, I also had the opportunity to participate in two demonstrations of this system for students, where they watched a short presentation on the topic and then did a one participant experiment.

Parallel to that, since the new study consists of using a new dry electrodes EEG system (which also means new pieces of hardware), I had to support professor Theodore on testing everything - including the new version of the software adapted to dry electrodes solution. Even further, I searched for methodologies to verify the stability of the system before the data collection and developed a code in Python to analyze the new report output implemented in this new version of the software (code available at github).

I was also able to participate in a few discussions and demonstrations of the new dry electrodes system solution with members of the Nice Pasteur Hospital team, which helped me understand better the limitations and concerns of using this new approach in practice. These types of discussions and demonstrations improved my knowledge on the topic and prepared me to run a few preliminary experiments with healthy participants and analyze the preliminary results, necessary for the Athena Team to be prepared to do the official experimental sessions with ALS patients.

Unfortunately, the experimental sessions with ALS patients were postponed for at least March because of the COVID-19 pandemic situation in France, making it impossible for me to participate of the data acquisition campaign.

2 - Materials and Methods

Since the goal of this project was to run a few preliminary experiments using the new dry electrodes EEG system solution in order to analyze the preliminary results obtained from it before re-performing the study carried out in [2], most of the methods followed the same principle. On the other hand, the fact that everything was done with new equipment implied some changes within the material.

2.1 - Experiment process

The experiment was performed by 4 different healthy participants in a total of 10 sessions. Each session lasted around 25 minutes, where the participant went trough three stages: set-up, calibration and copy spelling; while seated in front of a screen where the P300 speller keyboard was displayed [Figure 3].

Figure 3 - Healthy participant performing P300 Speller experiment.

During the set-up stage, the participant had the dry electrodes EEG cap put on (ANT Neuro Waveguard™ touch) from which 8 electrodes (FCz, Cz, C3, C4, CPz, Pz, P3, P4, grounded and referenced to left and right mastoid ECG electrodes, respectively) were connected to a eego™ mini-series amplifier (500-Hz sampling rate). As commented before, this material was different from the one used during the study made in [2]. Besides the usage of a different cap and amplifier, the number of the electrodes placed in the cap and their channels also changed. The reduction in the number of electrodes (from 12 to 8) was made to avoid using electrodes positioned in the back of the head, which caused discomfort for some ALS patients while resting their heads on the wheelchair headrests [Figure 4]. Another difference during this stage is that with dry electrodes EEG systems there is no necessity of applying gel. Instead of checking if the impedance level is low to verify the stability of the system before the start of the experiment, it is important to analyze if the impedance levels are stable [Figure 5].

In the calibration stage, participants had to focus on 11 letters, flashing 18 times each. Exactly as in [2], the recorded data was used to train spatial filters and the linear discriminant analysis (LDA) classifier [18].

Finally, during the copy spelling stage, the participant could select any word to type. While typing, participants were provided with cues (each keyboard letter to type briefly highlighted in blue) and feedback (letter highlighted in green if correctly selected by the P300 speller and in red otherwise) [2].

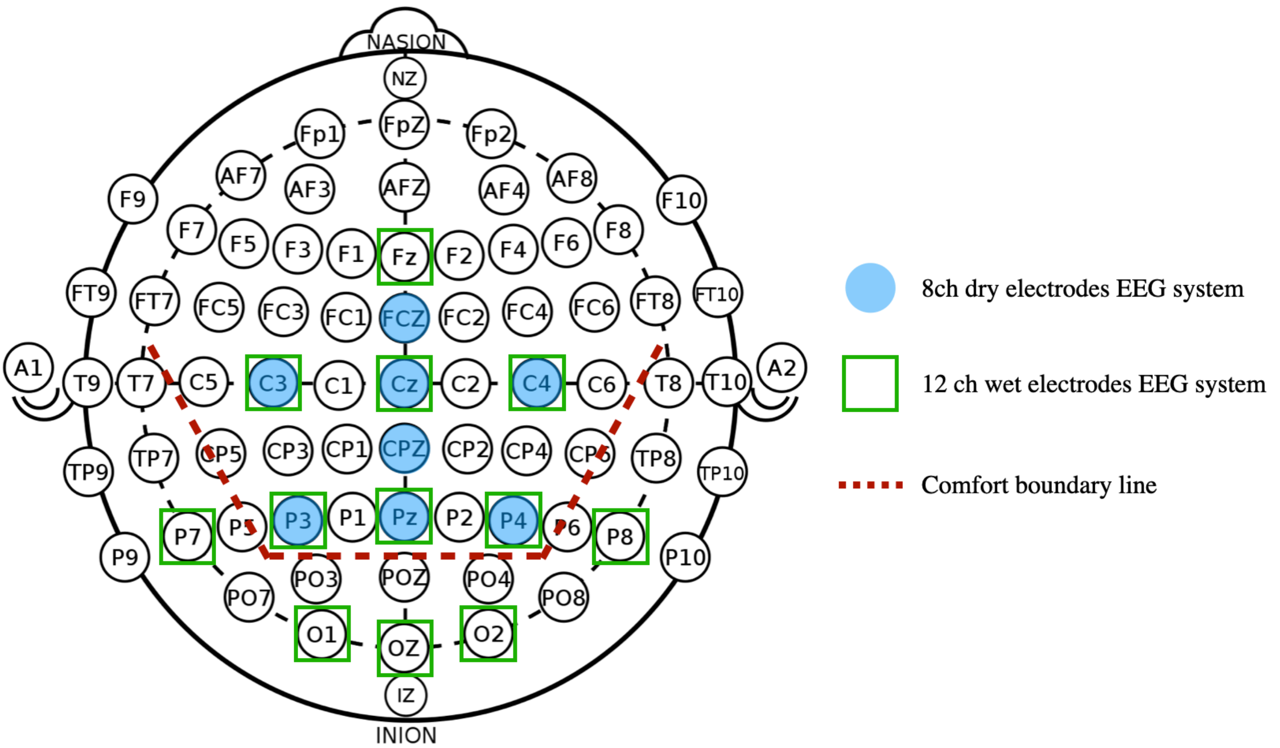

Figure 4 - Dry x Wet electrodes EEG cap positions comparison. The electrodes below the comfort boundary line are not being used anymore in the new dry electrodes EEG system. This change impacted the number and the position of electrodes placed in the new cap.

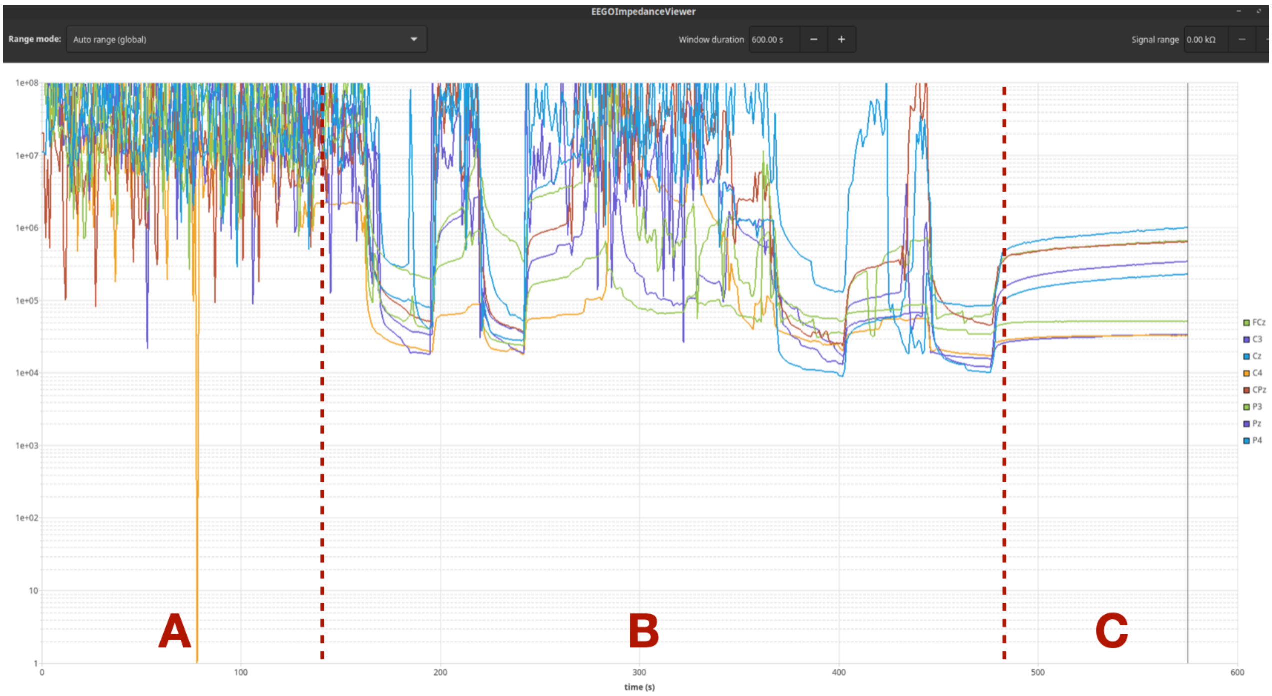

Figure 5 - Impedance stabilization process. [A] represents the initial moment of the set-up stage, where the cap is being put on the participant and the ECG mastoid electrodes are being placed. [B] is the period where the electrodes are being pressed and adjusted in order to make better contact with the scalp (sometimes it is also needed to put on a swimming cap on top of the EEG cap to reach a desirable contact). Finally, it is possible to observe in [C] when the impedances levels are stable and the participant is ready to move on to the calibration stage.

2.2 - P300 Speller system

This study was made using the P300 Speller system designed at Inria Sophia Antipolis [18], which functions on top of the OpenVibe platform - a software for EEG data acquisition and real-time processing [19]. To make P300 Speller possible, the system displays a keyboard containing 44 symbols (including letters, numbers, punctual marks and backspace).

Following the same approach as [2], the flashing procedure of the symbols consists of briefly covering the character with a "smiley face", as this has been shown to elicit stronger P300 responses than simply highlighting the character [20]. It also flashes the symbols in pseudo-random groups, designed to minimize the consecutive flashing of the same characters, and the simultaneous flashing of neighbor characters [21]. The flash duration interval was 50ms and the inter-stimulus interval was 250ms.

The P300 Speller system also counts with an early stopping procedure [22] based on symbol-based evidence accumulation. This means that if the classifier has 90% confidence that a specific symbol is the one being attended it sends a signal to the system to stop the flashing procedure and accept that specific symbol as the one being targeted by the participant. This type of mechanics helps to improve the number of symbols typed per minute, increasing the user's ability to communicate.

3 - Results

The objective of carrying out some preliminary experiments was to understand how the dry electrodes EEG system solution could reduce the technical and practical problems in working with wet electrodes regularly and if the results could reach a similar level of effectiveness as the wet electrodes system.

One first notable point is that while the set-up stage for the wet electrodes EEG system took around 13 minutes to be completed (range 6-30) [2], the new dry electrode system took, in average, 7 minutes (range 6-9). More than that, the dry electrodes solution does not require more than 1 minute to be dismantled and cleaned after the usage and does not require the participant to wash his hair.

For the calibration stage, there are no significant differences between the two solutions, as both follow the same methodology.

Table 1 presents a summary of the statistical results found for each session performed during the copy spelling stage of the experiment with the dry electrode EEG system. The 'Symbols to Spell' is the length of the word to type selected by the participant, the 'Correctly guessed rate'

Table 1 - Summary of copy spelling stage statistical results for each session with the dry electrode EEG system.

Participant	Trial Duration	Symbols to Spell	Correctly Guessed rate	Correctly Guessed Symbol per Minute	ITR	Flashes per Symbol Correctly Guessed
1	00:01:14	6	1,00	4,9	26,6	7,3
2	00:03:00	9	0,89	2,7	13,1	12,0
3	00:04:08	11	0,73	1,9	8,3	12,4
4	00:02:17	7	0,71	2,2	9,3	10,0
5	00:03:49	11	0,82	2,4	10,9	11,7
6	00:05:00	14	0,79	2,2	9,9	11,7
7	00:02:35	7	0,71	1,9	8,3	12,0
8	00:03:02	9	0,78	2,3	10,4	12,9
9	00:01:41	6	1,00	3,6	19,5	10,7
10	00:04:24	12	0,75	2,1	9,0	12,3

represents the percentage of symbols correctly guessed by the system (spelling accuracy rate), the 'Correctly guessed symbol per minute' gives an idea on how many symbols the participant would be able to type per minute using the P300 Speller, the 'ITR' (Information Transfer Rate - calculated with the Wolpaw formula [23]) is a metric calculated in bits/min that allows comparison between different types of systems and the 'Flashes per symbol correctly guessed' shows how many flashes in the targeted symbol were necessary, in average, to the system to accept that specific symbol as the one being targeted by the participant.

While the wet electrodes EEG system achieved an average of 97.5% (SD 3.5%) for the spelling accuracy rate during the copy spelling stage, the dry system solution could only reach an average of 81.8% (SD 11%). At the same time the solution used in [2] was able to correctly identify the targeted symbol with only, in average, 5.30 (SD 1.89) flashes, while the dry electrodes solution used in this study needed, in average, 11.30 (SD 1.63) flashes for performing the same task [Figure 6].

Also during the copy spelling stage using the dry electrodes EEG System, the mean for 'Correctly guessed symbols per minute' was 2.61 (SD 0.92) and the mean of ITR was 12.52 (SD 5.94). As the previous study did not publish the 'Correctly guessed symbol per minute' and 'ITR' metrics for the copy spelling stage, it is not yet possible to make a fair comparison between them. Fortunately, this analysis will be done during the next month when the new version of the software will receive an update where it will be possible to reprocess the experimental data collected in [2] and generate the new complete report (the same one that was used to analyze the experiments of the dry electrodes EEG system).

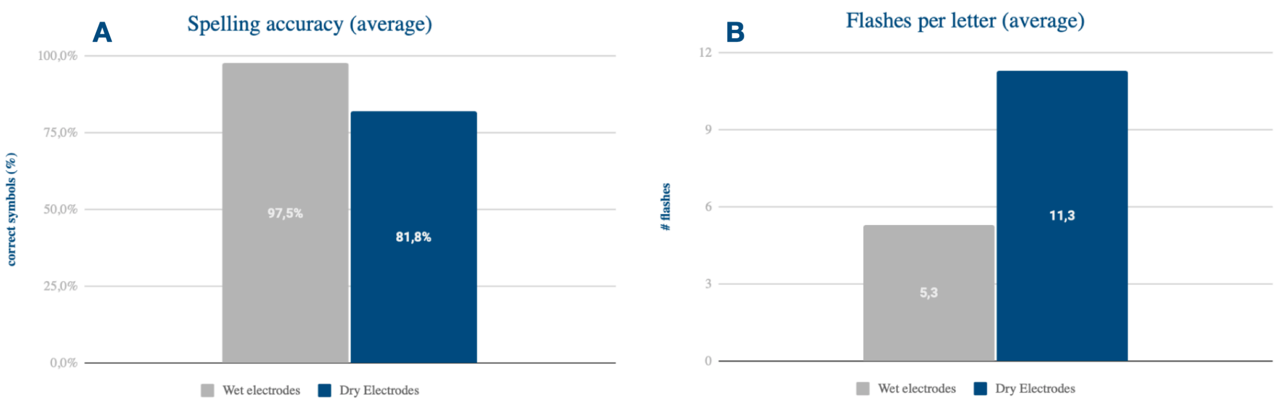

Figure 6 - Results comparison between Dry and Wet electrodes EEG systems during the copy spelling stage. The chart [A] provides the information that the average spelling accuracy rate decreased while working with dry electrodes and, at the same time, the chart [B] shows an increase in the number of flashes necessary to the system to correctly identify the targeted symbol.

4 - Discussion

Besides the clear improvement in the setting up times, the preliminary results obtained during this study with the dry electrodes EEG system could not reach the same level as the ones achieved by the wet electrodes EEG system in [2]. While the spelling accuracy decreased, more flashes were necessary during the typing process of P300 Speller. On the other hand, all the participants in every session were able to reach a level of accuracy over 70%, which shows that the application might still be controlled, but requires more effort by the user.

Even further, standard deviation metrics were also higher compared to the last study, suggesting that dry electrodes EEG caps may be more sensitive to different head shapes and/or hair styles. During some sessions, it was more difficult to achieve a good contact between the electrode and the participant's scalp (sometimes it was even necessary to wear a swimming cap on top of the EEG cap - greatly decreasing the participant's comfort level), bringing up the discussion of how important is to apply a specific amount of pressure to each electrode when working with dry electrodes. With this concern in mind, scientists have already started to experiment other approaches to the manufacture of EEG caps, including the production of customized caps for each participant individually, achieving an improvement on the results [24].

Another important consideration to take into account when directly comparing the results between this study and the one presented in [2] is the difference in the number of electrodes placed in the caps. It is unclear how this reduction might affect the results by itself. Also, during the copy spelling stage in this study the participant could choose any word to type, while during the same stage in the wet electrodes EEG system study, the participant had to choose between preselected 10-characters length long words.

Finally, it is relevant to note that all the experimental sessions in this study were done by healthy subjects and, due to the COVID-19 situation in France, 6 out of 10 sessions by the same participant.

5 - Conclusion

This study was able to verify the potential of using dry electrode EEG systems to allow individuals to communicate through a P300 Speller solution. The use of dry electrodes reduced technical and practical problems in working EEG systems, but did not achieve similar levels of results as in the previous study using wet electrode EEG systems.

In order to improve dry electrodes EEG solutions, a possible concern to be addressed is the development of EEG caps with an individual pressure regulating system for each electrode, instead of using the traditional standard sized fabric caps with fixed electrodes attached to it.

The experience gained during the preliminary experiments and the preliminary results of this study will support the Inria Athena project team and the Nice Pasteur Hospital in the upcoming data acquisition campaign with ALS patients.

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