Unleashing the Potential of HD-EEG

Are Sponge Electrode Caps the Future?

Master's Thesis

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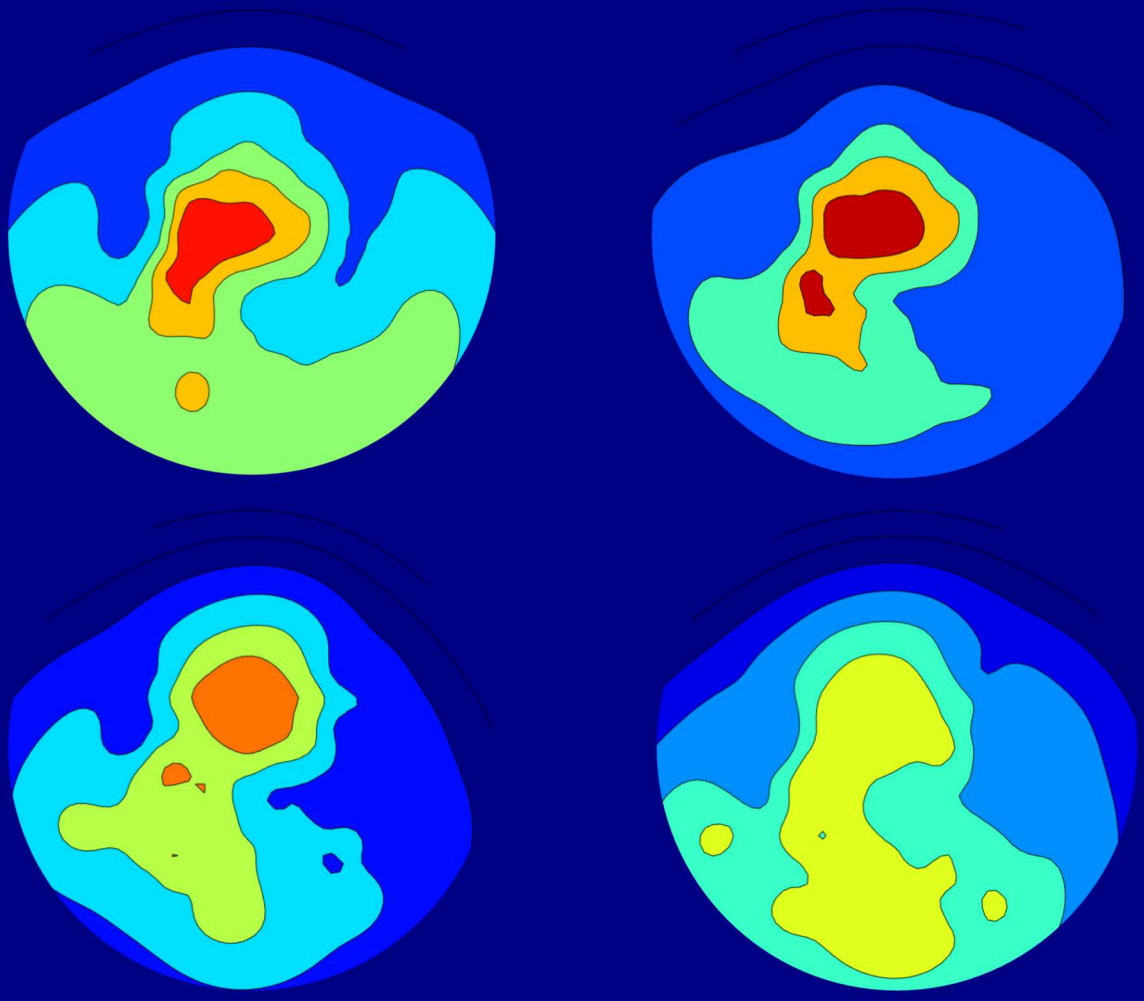
Delft University of Technology



TU Delft

Unleashing the Potential of HD-EEG

Are Sponge Electrode Caps the Future?

by

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TU Delft

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Marjolein G. Scheffers
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Unleashing the Potential of HD-EEG: Are Sponge Electrode Caps the Future?

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***Abstract* - Currently, electroencephalography (EEG), high-density EEG (HD-EEG) in particular, is not used to its full potential in clinical settings. To overcome the limitations of the state-of-the-art gel-electrode EEG, new types of EEG electrodes are developed. The objective of this study is to evaluate the performance of a high-density sponge electrode cap, compared to a high-density gel electrode cap, both with 128 equidistant electrode-layouts. Therefore, the mechanically evoked steady-state response (MSSR) was recorded from ten participants with both caps in a wrist joint manipulation experiment. Cap performance was compared regarding feasibility, data quality, and test re-test reliability, in a quantitative and qualitative way. We found that the *feasibility* of the sponge cap is significantly better than that of the gel cap, that the *data quality* of the sponge and gel cap is qualitatively comparable, and that the *test re-test* reliability of the sponge cap is fair to good. Sponge EEG caps therefore may offer the solution for the underutilization of low and high-density EEG.**

***Index Terms* - EEG; HD-EEG; Sponge electrode; Gel electrode; EEG electrode comparison**

I. Introduction

Electroencephalography (EEG), high-density EEG (HD-EEG) in particular, is not used to its full potential in clinical practice, despite its distinguishing qualities of high temporal resolution (millisecond range) and low costs compared to other neural imaging methods such as MRI [1] [2] [3] [4]. EEG measures the surface potentials of the scalp between a measurement electrode and a reference electrode, both with respect to a common ground electrode. The number of measurement electrodes ranges between one and 256, depending on the objective. EEG with over 128 electrodes is considered high-density EEG and is used for source localization [5].

The EEG electrodes currently used are usually applied in the time-consuming process of precisely placing the electrodes on the scalp one by one and require a gel electrolyte at each electrode to lower the electrode-skin impedance to minimize noise [6]. Even though the electrode-placing issue is sometimes resolved by using electrodes embedded in a cap [7], the use of the gel electrolyte still imposes limitations on EEG measurements: time-consuming preparation, laborious cleanup, and only staff trained in EEG can perform these measurements. Hence, EEG and HD-EEG in particular, are underutilized.

A clear example of the underutilization of EEG is found in the Dutch guideline of the treatment and rehabilitation of stroke [8], where EEG is only mentioned in the context of rTMS, even though many studies show the value of using EEG (64 and 20 electrodes) as a diagnostic tool after stroke [3] [9] [10]. Underutilization of HD-EEG is apparent in epilepsy, where it can be used for the localization of the epileptogenic cortex with long-term EEG protocols [5] [11]. In long-term EEG, patients are admitted to the hospital for periods of 24 hours up to two weeks for provocation and recording of an epileptic seizure to locate its source [12]. Short-term HD-EEG is a promising tool for the early diagnosis of Alzheimer's Disease [13] [14], and for the measurement of evoked potentials as a biomarker for disease progression, for example in multiple sclerosis [15]. However, the disproportional preparation time prevents HD-EEG to find its place in clinical practice. Therefore, the challenge is to find and implement a feasible alternative for gel-electrodes.

Fortunately, the gel-electrode limitations and the known potential of EEG have led to the development of gel-free EEG electrodes. For example, dry electrodes, that rely on direct electrode-skin contact, have been developed in varying shapes (flat adhesive patches, pin-shaped, spider-shaped, and brush electrodes) and materials, such as semiconductors, metals, and metal-filled polymers [16] [17]. Studies comparing gel- and dry EEG systems show drastic decreases in preparation time for the dry electrodes and high comparability in signal quality [16] [18]. However, dry electrodes are reported to be uncomfortable compared to gel electrodes; prone to movement artifacts in dynamic measurements [18]; and the electrode-skin impedance changes when the user is sweating, negatively influencing signal quality [16] [17].

The sponge electrode is an alternative, gel-free electrode, made from materials such as carbon fiber-based conductive silicone sponge [4] or silver-nanowire/PVB/melamine sponge [17]. These sponge electrodes are soaked in water or a saline solution before use, to establish low electrode-skin impedance. A clinical study comparing a sponge EEG system

(24 channels) with a gel EEG system (32 channels), shows shorter preparation times of the sponge EEG with respect to gel EEG and the same physiological and pathological outcomes for the sponge EEG and the gel EEG from visual inspection of the EEG data [19].

The objective of this study is to compare the applicability of high-density gel and sponge-based EEG caps. Therefore, the two caps were quantitatively and qualitatively compared based on feasibility, data quality, and test re-test reliability. The specific caps used in this study were the Waveguard original and the Waveguard net, both having a 128 equidistant electrode-layout manufactured by ANT-Neuro b.v. (Hengelo, Netherlands). With both caps, a mechanically evoked steady-state response (MSSR) is recorded in ten participants performing four sessions each (two with each cap). The data are automatically pre-processed and analyzed with EEGLAB in Matlab. Finally, the results of both caps are compared within the study and with prior research.

II. Materials and Methods

A. Participants

Ten healthy participants (4 females and 6 males; M = 25 years, S.D. = 2,3) participated in the study. The EEG data from one sponge session were considered unreliable because of significant deviation from all other datasets and were therefore excluded from the analysis (**Appendix V-A**). To keep the number of gel and sponge sessions equal, the EEG data from one gel session from the same participant were also excluded. The impedance data and feasibility data of these sessions remained in the analysis. All participants had normal or corrected-to-normal vision and no neurological problems. The participants were asked to have washed and dried hair before each session. They provided written informed consent prior to the experiments and received financial compensation for their participation. The study has been approved by the Human Research Ethical Committee of the TU Delft.

B. Materials

The mechanically evoked steady state response (MSSR) at the cortex was evoked using a robotic manipulator (Wristalyzer, MOOG, Nieuw-Vennep, The Netherlands)(**Figure 1**).

For the EEG data acquisition, the Waveguard^{TM}original electrode cap and the Waveguard^{TM}net were used for the gel and sponge measurements respectively. Both caps have 128-electrode equidistant electrode layout (**Figure 2**) and are manufactured by ANTneuro b.v. (Hengelo, Netherlands). The gel-cap and the sponge-cap data acquisition was done using two cascaded 64-channel **eego**^{TM}mylab amplifiers (https://www.ant-neuro.com/products/eego-mylab) sampling at 2048 Hz and with an input impedance of 1GΩ.

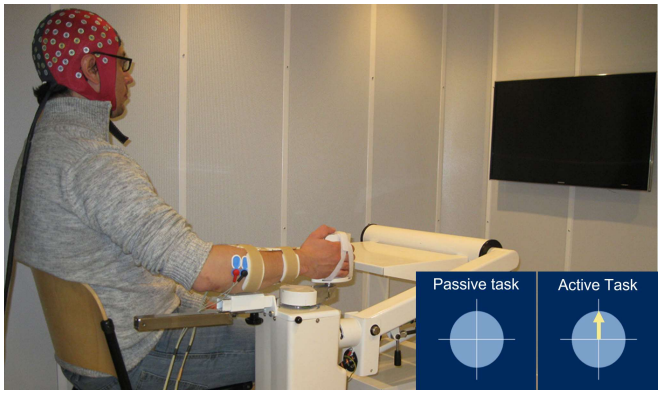

Fig. 1: Experimental Setup. Participant wears EEG cap while staring at a screen displaying either passive or active task visual feedback. The lower right arm and hand are strapped to the handle of the haptic manipulator [3]

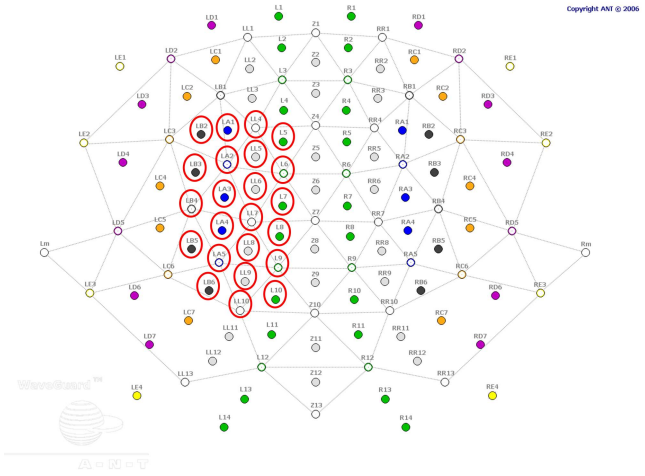

Fig. 2: Equidistant electrode layout of both gel and sponge cap with the 126 electrodes used in the analysis (2 electrodes were excluded from both caps (**Section II-E**)). Electrodes laying over the sensori-motor cortex are marked red and form the region of interest (ROI). Consult **Appendix V-B** for comparison with equidistant electrode layout [20]

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C. Experimental protocol

Four measurement sessions were performed per participant, two with the gel-based electrode cap and two with the sponge cap, all at least one day apart, at the same time of the day. Gel and sponge caps alternated each session, and the session order was counterbalanced across participants. By carrying out two sessions per cap per participant, the test re-test reliability of both caps could be determined. The measurements were performed in a soundproof chamber for constant conditions during all sessions.

The size of both caps was based on the circumference of the participant's head. Once the cap was placed correctly, the participant took place in the experimental setup (**Figure 1**) for impedance optimization and recording.
The gel cap was applied according to expert instructions.

Electrolyte gel was applied to each electrode to optimize electrode-skin impedance. The impedance optimization continued until all electrodes had an impedance of <20kΩ or when 45 minutes had passed due to time limitations.

The sponge cap was applied according to the user manual: before application, it was soaked for 10-15 minutes in a saline solution of two liters of water with two teaspoons of potassium chloride (KCl) and two teaspoons of baby shampoo. Once the participant was seated in the experimental setup, the impedance was checked and optimized. Electrodes with high initial impedance were wiggled such that the hair underneath was moved aside. When a wide range of electrodes had high impedance, the net was wiggled as a whole as in the manual. A maximum of ten minutes was taken for impedance optimization since that was the indicated application duration by the manufacturer.

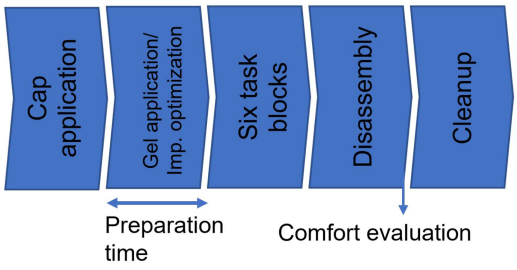

Fig. 3: Session progress from left to right for gel and sponge sessions. Gel application step is only applicable for the gel cap sessions.

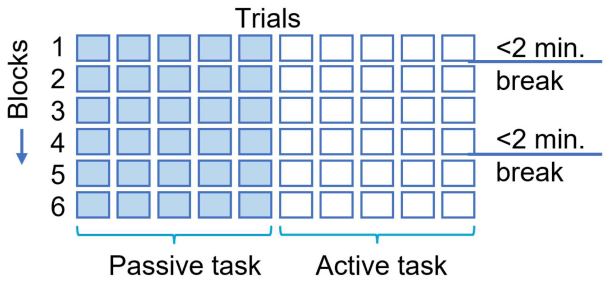

Fig. 4: Six blocks of ten trials, e.g. the first block consists of five times passive task, then five times a passive task, followed by a two-minute break.

For the active task, the participants were asked to maintain a wrist flexion torque of 1 Nm, for which they received visual feedback (**Figure 1**, active task).

The preparation time was measured from the moment the cap was correctly placed on the participant's head till the impedance optimization was finished (**Figure 3**). After cap application, gel application (only for the gel cap), and impedance optimization, the mechanically evoked steady-state response (MSSR) was recorded. The MSSR was measured in six blocks consisting of ten trials: five times a passive and five times an active upper limb task (**Figure 4**). Half of the participants started with the passive task, and the other half with the active task. The participants had to gaze at the center of the circle at the screen in front of them while seated relaxed (**Figure 1**). During both tasks, the robotic manipulator applied repeated multisine perturbations to the right wrist to provide sensory stimulation and challenge task execution. For the passive task, the participants were instructed to relax and ignore the perturbations to the wrist.

After each session, participants rated their comfort level on a Likert scale (1 - very uncomfortable, 6 - extremely comfortable) during electrode preparation and recording. The cleaning of the gel cap consisted of going over each electrode with running water and a brush to remove the gel. The cleanup time of the gel cap was measured in six sessions. The cleaning of the sponge cap consisted of submerging the cap in fresh water with soap three times. The cleanup time of the sponge cap was estimated. Both caps were dried on a drying rack.

D. Disturbance signal design

During both the passive and active tasks the robotic manipulator applied the same continuous periodic angular disturbance signal to the wrist (**Figure 5**). The disturbance signal was a random-phase multisine signal designed at a sampling rate of 2048 Hz:

$$r(t) = \sum_{k=1}^{N-1} A_k cos(2\pi f_0 kt + \phi_k) \quad (1)$$

In which k is the frequency, A_k the amplitude at frequency k, ϕ_k the phase at frequency k, f_0 is the frequency resolution in [Hz], N is the number of samples in one period and t is the time vector describing one period of the signal [3]. The fundamental input frequency was 0.8 Hz, resulting in a period of 1.25 s. The excited harmonies were 1-8, 10, 12, 14, 17, 20, and 24, corresponding with frequencies k of 0.8, 1.6, 2.4, 3.2, 4.0, 4.8, 5.6, 6.4, 8.0, 9.6, 11.2, 13.6, 16.0, and 19.2 Hz. Every trial (for both passive and active task) contained ten periods, resulting in a trial duration of 12.5 s.

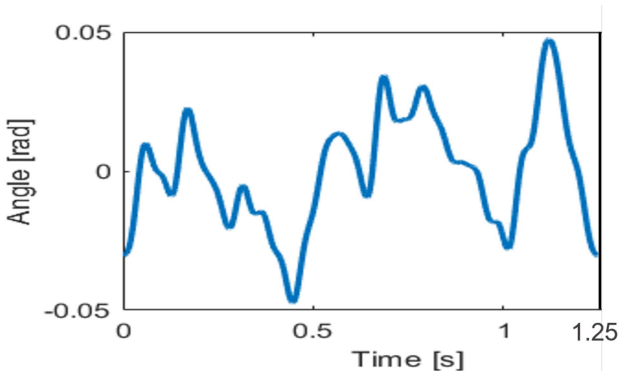

Fig. 5: One period of the multisine disturbance signal used in both passive and active tasks. Each trial consists of ten times this period. A total of 300 periods were recorded per task.

E. Data pre-processing

Data preprocessing was done in Matlab R2022a, using EEGlab. From the 128 electrodes, 126 electrodes were used for comparison, since the gel cap lacked the LL14 and RR14 electrodes, and the sponge cap lacked the Z14 electrode. The first two periods of each trial were not included in the analysis, to prevent the contribution of settling artifacts.
Then, the EEG data were bandpass filtered with a 4th order Butterworth filter between 0.5 Hz and 40 Hz and then resampled to 256 Hz. Bad channels were identified and rejected based on electrode-skin impedance and channel variance. The impedance threshold for the gel-cap data was set to 20 kΩ; taking into account values from literature [21]. Because of the unavailability of literature about a suitable impedance threshold for sponge electrodes, this was set to a relative threshold based on the threshold for the gel cap (**Appendix V-C**).

The variance threshold for channel rejection was set to three times the standard deviation on top of the mean [22] for both the gel cap and the sponge cap. After channel rejection, the EEG-data was re-referenced to an average reference. The last step was to interpolate the removed channels, using spherical interpolation. No artifact rejection was applied and all epochs were used.

F. Data analysis

This section describes the outcome metrics used to analyze the feasibility, data quality, and test re-test reliability of the sponge-cap and the gel-cap.

Feasibility - In order for an EEG electrode cap to be feasible, it should be time efficient for the user and comfortable for the wearer. Therefore, the feasibility is evaluated by the preparation time, and the cleanup time, both measured as indicated in **Figure 3**, and the subjective comfort level of the participant over the full measurement, including cleaning of the head. The comfort level was rated on a Likert scale; 1 indicating not comfortable at all, and 6 indicating extremely comfortable.

Data quality - The data quality was evaluated based on (1) the number of bad channels, (2) the electrode stability, and (3) the signal-to-noise ratio (SNR) in the frequency domain. Furthermore, the relation between impedance and SNR is investigated.

(1) The number of rejected channels depends on the impedance values and on the variance of the channels. Since the threshold for impedance was a relative value for the sponge cap, the magnitude of the threshold is taken into account.

(2) The electrode stability of the caps is the difference between the impedance at the end and the beginning of the recording, corresponding to the change in impedance over a 30-minute period. Rejected channels and channels with impedance values higher than 10 MΩ after recording were not included in the analysis.

(3) The last, and most important data-quality metric is the signal-to-noise ratio (SNR). The SNR is used as a metric to determine how much of the cortical signal (at electrodes) shows the expected response associated with the perturbation signal and was calculated in the frequency domain as signal power over signal variance averaged over the perturbation signal input frequencies (**Section II-D**). The steady-state signal power is the signal power averaged over all the recorded periods:

$$\hat{E}_X(f) = \left| \frac{1}{P} \sum_{p=1}^{P} X^{[p]}(f) \right|^2 \tag{2}$$

The variance was calculated with:

$$\hat{\sigma}^2_X(f) = \frac{1}{P(P-1)} \left| X^{[p]}(f) - \frac{1}{P} \sum_{p=1}^{P} X^{[p]}(f) \right|^2 \tag{3}$$

In **Equations 2** and **3**, P is the total number of recorded periods, $X(f)$ is the Fourier transformed EEG signal of each recorded period p. Taking **Equations 2** and **3** and averaging over the input frequencies, leads to the equation for the SNR:

$$SNR = \frac{1}{F} \sum_{f \in F} \frac{\hat{E}_X(f)}{\hat{\sigma}^2_X(f)} \tag{4}$$

In which F are the perturbation input frequencies (**Section II-D**).
The SNR was calculated per electrode and analyzed both qualitatively and quantitatively. Qualitative analysis is performed by visual analysis of the topographs representing the average SNR of the 19 gel measurements and 19 sponge measurements at each electrode. To compare SNR values obtained from the gel and sponge cap, the percentage deviation of the active task with respect to the passive task was calculated for both caps:

$$\Delta SNR\%_{tasks} = \frac{SNR_{PT} - SNR_{AT}}{SNR_{PT}} * 100\% \tag{5}$$

Where SNR_{PT} and SNR_{AT} are the average SNR values of the passive task and active task measurements per electrode. This equation was applied to the gel cap and the sponge cap. For the quantitative evaluation of the SNR, a region of interest (ROI) was defined, consisting of 23 electrodes positioned over the left sensorimotor cortex, where the cortical response associated with the perturbations of the right wrist is expected. The selected electrodes are L5-L10, LL4-LL10, LA1-LA5, and LB2-LB6. In **Figure 2** these electrodes are marked red.

Test re-test reliability - The test re-test reliability is defined as the variation in measurements taken by an instrument on the same subject under the same conditions [23]. The intraclass correlation coefficient (ICC) was used to quantify the test re-test reliability of the average SNR values of the electrodes in the ROI for the passive task and active task in the gel cap and in the sponge cap.

G. Statistical analysis

Paired samples T-tests with a significance level of 0.05 were performed in Matlab to statistically compare gel and sponge cap performance in the comfort level, preparation time, and average SNR in the region of interest.

For the test re-test reliability, the ICCs were calculated with two-way random effects, absolute agreement, single rater formula, ICC(2,1), where the ratio of the variance between participants to the variance between participants plus error variance was calculated. Values less than 0.4 indicated poor reliability, between 0.4 and 0.75, fair to good reliability, and higher than 0.75 are indicative of excellent reliability [23].

III. Results

The results will be presented in the three categories used for comparison of the gel cap and the sponge cap: first feasibility (preparation time, cleanup time, and comfort level), then data quality (bad channels, electrode stability, and SNR), and finally test re-test reliability (ICC).

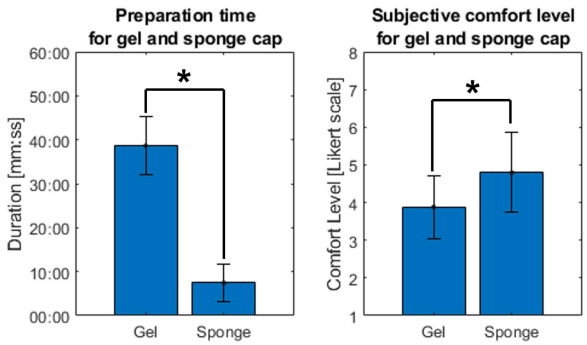

Fig. 6: Left: Preparation duration (p<0.001). Right: Comfort level of participants on Likert scale (p=0.01). 1 - not comfortable at all, 6 - extremely comfortable. The star * indicates p<0.05.

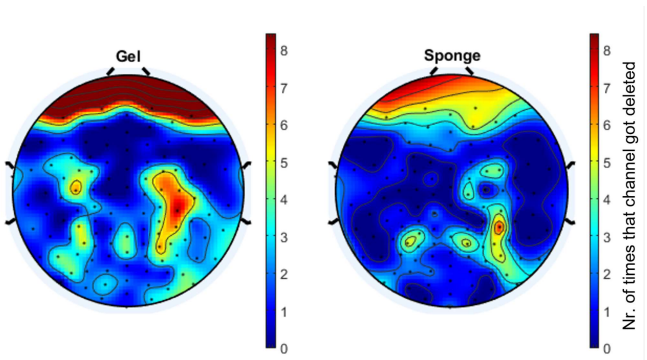

Fig. 7: Topographical representation of the number of measurements that a channel is rejected. Channels in the frontal area are rejected more often in both the gel and sponge cap.

A. Feasibility

The average preparation time of the gel cap was 38.7 ±7.14 min compared to a preparation time of 7.45 ±4.14 min (p<0.001) for the sponge cap (**Figure 6**). The limits of 45 and 10 minutes for the gel and sponge cap application were reached six and seven times respectively.
The average comfort level of the gel cap was 3.9 ±0.8 and 4.8 ±1.1 on a Likert-scale (1 - very uncomfortable, 6 - extremely comfortable) for the sponge cap (p=0.01) (**Figure 6**).
The cleanup time was measured for six gel measurements and had an average value of 18.9 ±1.7 min. The cleanup time for the sponge cap was not measured but was estimated to take less than 3 min in all sessions.

B. Data quality

Bad Channels - The impedance threshold of the sponge cap θ_{sp}, calculated in **Appendix V-C**, was 156 kΩ. For this calculation, 37 channels from five sessions with an impedance greater than 1000 kΩ were excluded. The number of standard deviations n that the gel threshold was away from the average impedance, required for **Equation 7**, was 0.9. For this calculation (**Equation 6**), seven channels from five sessions with an impedance value greater than 500 kΩ were excluded.
The average number of channels rejected with the gel cap because of **impedance** values higher than the absolute threshold of 20 kΩ was 12.4 ±14.0, and the average number of channels in the sponge cap greater than the average relative threshold of 156 kΩ was 15.05 ±24.6 (p=0.61). However, for the sponge cap, the threshold was raised to a relative threshold (**Equation 8**) when the average impedance value of a measurement was greater than 156 kΩ. For six sponge measurements from four participants, the threshold was raised to relative thresholds, ranging between 165 kΩ and 589 kΩ. The average number of rejected channels with these thresholds was 8.9 ± 12.4 (wrt gel: p=0.26).
The average number of channels rejected in the gel measurements because of **channel variance** higher than the relative threshold of three times the standard deviation plus the mean was 2.5 ±1.7. The average number of channels in the sponge cap greater than the relative variance threshold was 1.7 ±1.6 (p = 0.032).
The total number of rejected channels is 14.9 ±13.7 for the gel cap and 10.6 ±11.8 for the sponge cap (p=0.12).
In **Figure 7** the total number of measurements that a specific channel was rejected is displayed. In both caps, the frontal electrodes are rejected most often.

Electrode Stability - The electrode stability was quantified as the impedance difference between before and after recording. The average impedance difference of all electrodes of the gel cap is 5.3 ±21.2 kΩ compared to 63.5±83.2 kΩ for the sponge cap (p<0.001)(**Table I**). **Figure 8** shows the average difference in impedance per electrode.

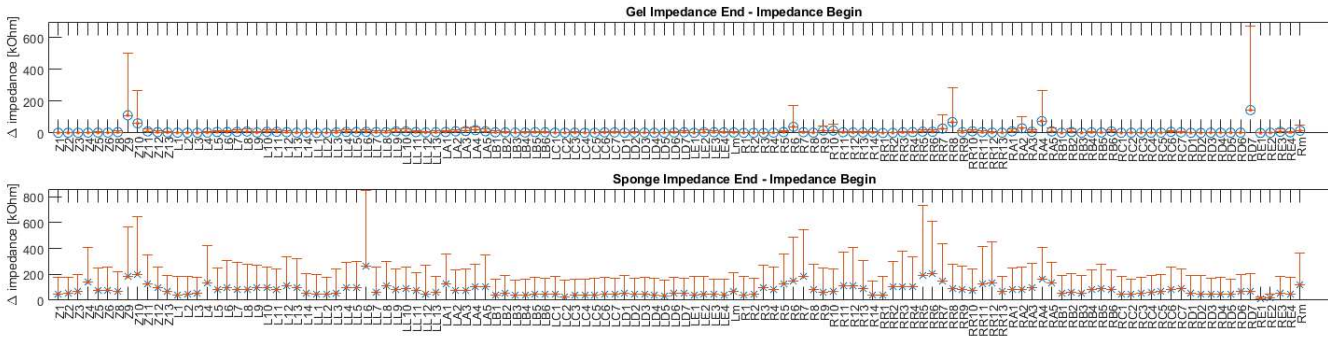

Fig. 8: Electrode Stability. Averaged difference in impedance at the end of the session and the beginning of the session over all gel (top) and sponge (bottom) sessions. Zero difference means good electrode stability. For better visibility at the y-axis, only the positive standard deviation is plotted.

	Imp begin [kOhm]	Imp End [kOhm]	Δ[kΩ]	Δ%
Gel	5.9 ±4.9	11.2 ±61.7	5.3 ±21.2	+89
Sponge	62.1 ±68.0	125.6 ±214.9	63.5 ±83.2	+102

Table I: Electrode stability. Impedance values and differences before and after recording. p < 0.001 for Δ_{gel} vs Δ_{sponge}.

SNR - **Figures 9** and **10** show the topographical distribution of the mean SNR for the 19 measurements with the gel cap and 19 measurements with the sponge cap. Comparable SNR patterns from the gel and sponge caps can be observed, meaning that the cortical response associated with the perturbations of the right wrist that is measured with the gel cap, is also measured with the sponge cap. However, there are also some differences between the figures. The high SNR region of the sponge cap lies more frontal and less to the central left than the gel cap. Additionally, the occipital left and median region of the sponge cap show increased SNR when compared to the gel cap. Moreover, the difference between the passive and active task is bigger in the high SNR region of the sponge cap compared to the gel cap. In the quantitative analysis of the average SNR in the ROI for the passive task is -17.0 ±2.5 dB for the gel cap and -18.4 ±2.7 for the sponge cap (p<0.001) and for the active task -17.4 ±2.4 for the gel cap, and -18.7 ±2.6 for the sponge cap (p=0.002) (**Table II**).

Figure 11 shows the percentage deviation of the active cap with respect to the passive task for both caps. Again a comparable pattern can be observed for both caps. A difference that can be observed in the frontal region is that the gel cap shows a bigger deviation of the active task from the passive task than in the sponge cap. The occipital region shows a bigger deviation of the active task from the passive task in the sponge cap compared to the gel cap.

	SNR PT [dB]	SNR AT [dB]
Gel	-17.0 ±2.5	-17.4 ±2.4
Sponge	-18.4 ±2.7	-18.7 ±2.6

Table II: The average SNR values of the electrodes in the ROI for the passive task (p< 0.001) and active task (p=0.002) for both caps. PT = passive task, AT = active task.

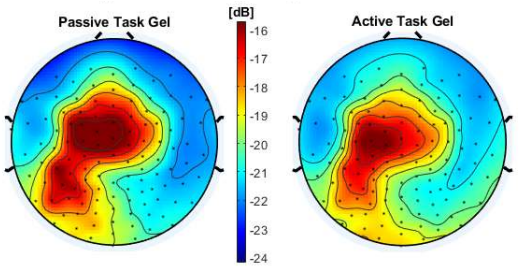

Fig. 9: Average SNR of 19 **gel-cap** measurements in both passive and active task on a [dB] scale. Note that the highest SNR is found in the channels overlaying the sensorimotor cortex.

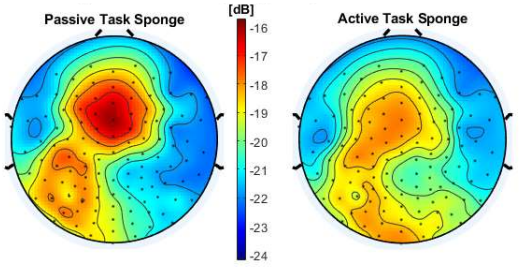

Fig. 10: Average SNR of 19 **sponge-cap** measurements in both passive and active task on a [dB] scale. Lower SNR in active task than in passive task.

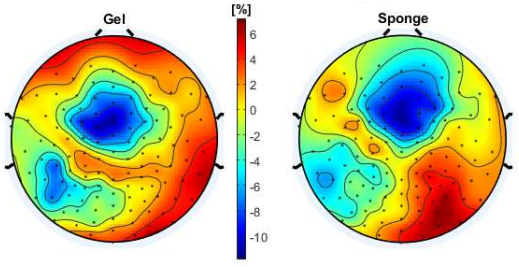

Fig. 11: Average deviation in SNR of active task from passive task in [%] in both caps. Note that the gel and sponge cap show a similar SNR-difference pattern between the active and passive task.

C. Test re-test reliability

In the active task, the test re-test reliability of the average SNR in the ROI was comparable for the gel cap and sponge cap, with ICCs of 0.60 and 0.55, respectively, indicating fair to good test re-test reliability. In the passive task, the ICC of the gel cap was higher (0.80, indicating excellent test re-test reliability) than that of the sponge cap, however, with an ICC of 0.58, the test re-test reliability of the sponge cap is still considered fair to good.

IV. Discussion

This study evaluated the performance of an equidistant high-density sponge-cap with respect to a gel-based cap by comparing feasibility, data quality, and test re-test reliability in both a quantitative and qualitative way. EEG data were collected from ten participants with a wrist joint manipulation protocol measuring the mechanically evoked steady-state response (MSSR). We found that the *feasibility* of the sponge cap is significantly better than that of the gel cap, that the *data quality* of the sponge and gel cap is qualitatively comparable, and that the *test re-test* reliability of the sponge cap is fair to good. These findings hold significance and will now be discussed in further detail.

A. Discussion of the results

Feasibility - In this study, the average preparation time of the sponge cap was 7.45 ±4.14 min compared to a preparation time of 38.7 ±7.14 min for the gel cap ($p<0.001$), corresponding to a 79% shorter preparation time of the sponge cap than the preparation time of the gel cap. Similarly, a prior study reported a 62% reduction in preparation time for a sponge cap with 24 electrodes compared to gel EEG with 32 loose electrodes [19]. The greater application advantage of the sponge cap over the gel cap in our study compared to the previous study is assumed to be due to the higher number of electrodes used, illustrating the growing advantage of sponge EEG with the number of electrodes used.

Even though the cleanup time was not consequently measured in the gel cap and estimated for the sponge cap, the faster sponge cleanup can be interpreted as support of the general time efficiency of the sponge cap. Another comment on the cleanup and hygiene of the caps, is that the sponge cap does not require scratching of the skin with a bolt needle, which is required in the gel cap. This limits the infection risk with the use of the sponge cap compared to the gel cap.

The overall comfort level on a Likert-scale was rated at 3.9 ±0.8 for the gel cap, and 4.8 ±1.1 for the sponge cap. No other studies evaluated the comfort of the sponge cap compared to the gel cap, however, comfort evaluation of dry electrodes compared to gel electrodes has been carried out and resulted in lower comfort levels of the dry electrodes compared to gel electrodes [18] [16]. Advocating for sponge electrodes over dry electrodes as an alternative for gel electrodes when it comes to wearing comfort.

In clinical practice, the better feasibility (shorter preparation times and more wearing comfort) of the sponge cap compared to the gel cap, is not only advantageous, or crucial in some cases, for the medical staff, but also enables EEG measurements to be conducted in patients that cannot endure long preparation time or discomfort of the gel cap.

Data quality - There was no significant difference between the number of rejected channels in the gel cap (14.9 ±13.7) and in the sponge cap (10.6 ±11.8)($p=0.12$), supporting the validity of the comparison between the caps. Kam et al. [18] used a different approach, and visually identified and rejected all channels with 'excessively noisy signals'. Compared to Kam et al. [18], the percentage of rejected channels in the gel cap is higher in our study (3±2% vs 12±11%) and the percentage of sponge electrodes rejected in our study (8±9%) was lower than the percentage of dry electrodes rejected (16±7%) by Kam et al. These different results reflect the different choices of the researchers more than the differences in data quality.

The electrode stability, was significantly better in the gel cap (5.3 ±21.2kΩ) than in the sponge cap (63.5 ±83.2kΩ) ($p<0.001$), corresponding with a percentage increase of 89% (gel) and 102% (sponge). Fiedler et al. [16] reported an average increase of just 7% for dry electrodes (begin: 532±199kΩ, end: 568±202kΩ), and a 21% *decreased* impedance for gel electrodes (begin: 23±18kΩ, end: 19±14kΩ). Compared to Fiedler et al, the larger standard deviation in this study is apparent. This might be due to bigger cohort size of Fiedler (30 participants). Furthermore, the lower absolute impedance values of the sponge cap compared to the gel cap are noticeable, however, the relation between impedance and SNR is weak (but significant) so the magnitude of the impedance does not strongly affect the SNR values (**Appendix V-D**, [24]). The lower electrode stability of the sponge cap compared to the gel cap has the implication that long-term EEG is not possible with sponge EEG; which is confirmed by the manufacturer of the sponge cap by only guaranteeing a measurement window of three hours before evaporation of the saline solution in the electrode sponges.

Although the quantitative comparison of the average SNR in the ROI showed significantly better SNR of the gel cap (-17.0 ±2.5 dB and -17.4 ±2.4 dB) compared to the sponge cap (-18.4 ±2.7 dB and -18.7 ±2.6 dB) in both the passive and active tasks ($p=<0.001$ and $p=0.002$), the sponge cap's lower SNR values do not imply the inability to provide the required information. Especially, since the qualitative analysis of the average SNR shows comparable patterns in both tasks (**Figures 10** and **9**) and furthermore, the percentage deviation of the active task from the passive task also shows a comparable pattern in both caps (**Figure 11**). These results correspond to the clinical trial of Gunther et al [19], reporting the same physiological and pathological outcomes for the gel and sponge EEG from visible inspection of the EEG data. However, in the averaged SNR plots, the sponge cap does slightly deviate from the gel cap in the occipital left and median region, where the SNR in the sponge cap is higher

than the SNR in the gel cap. This might indicate that the sponge cap is more sensitive to muscle artifacts from the neck than the gel cap.

We analyzed the data quality based on bad channels, electrode stability, and SNR. However, since the comparative nature of this study, we need to discuss the exclusion of one sponge EEG dataset. This dataset was excluded because the SNR in the passive task in the ROI deviated significantly from the mean SNR of all sponge **caps in the passive task (Z-score = 3.1, Appendix V-A**). Therefore the EEG data of this session was considered unreliable and excluded from the analysis. Although not quantitatively investigated, we presume that the unreliability of the dataset is related to the type of hair of this participant. The other sponge session with this participant is included in analysis but was close to being deemed an outlier as well (Z-score = 1.9). The supposed effect of hair type on the sponge cap performance is opposed to a qualitative statement of Gunther et al ([19]), stating that sponge EEG was still feasible in participants with dense or curly hair.

Test re-test reliability - The test re-test reliability of the sponge cap was slightly lower than that of the gel cap, but still fair to good. In clinical practice, good test re-test reliability could be important for example in monitoring disease progression with HD-EEG biomarkers. We consider the proximity of the sponge ICCs to the gel ICCs promising and recommend taking test re-test reliability into account for performance evaluation.

B. Methodological considerations

This comparative study was limited by the small cohort size of ten participants, which may have contributed to the big standard deviations of the number of rejected channels and electrode stability. The measurements were performed in a controlled laboratory environment, reducing the number of varying factors for a clean comparison between the gel and sponge cap, but not reflecting the use of EEG outside the laboratory.
Furthermore, the preprocessing of the EEG data needs to be discussed. First, bad channels were identified automatically. Considering the amount of data, this is essential for the implementation of HD-EEG in clinical practice. Algorithms for automatic bad channel rejection have been developed for gel EEG [22] [25] [26], however, the different impedance characteristics of sponge EEG require adjusted methods. Secondly, the preprocessing of the EEG data was conservative; no epoch or artifact rejection was applied. Artifact rejection with independent component analysis could reduce the effect of the eye- and muscle artifacts, which might bring the performance of the gel and sponge cap even closer together.
Lastly, the analysis of the data was conducted in group form, as opposed to individual dataset analysis, reflecting the use of EEG in research better than in clinical practice.

C. Future research

Future research into the applicability of high-density EEG sponge caps in clinical practice should have bigger cohort sizes and establish the conditions, hair type in particular, for good sponge cap performance. We suspect that dense, curly, and/or long hair in some cases negatively affects the reliability of the sponge cap performance. How this relates to the effect of hair type on gel cap reliability should be studied. The use of steady-state evoked potential protocols, like the one used in our study, is recommended for future studies since the SNR increases with more repetitions of the same stimulus, hence more repetitions of a stimulus with a sponge cap could compensate for slightly lower signal quality compared to the gel cap. These evoked potentials could function as reliable biomarkers for diagnosis and disease progression in routine clinical practice [15]. Additionally, state-of-the-art signal processing methods might bring the gel and sponge cap performance even closer. Furthermore, the quality of source localization with the sponge cap should be investigated, to fully use the capacities and advantages of the high-density sponge cap. Lastly, clinical trials are required to investigate whether the high-density sponge cap adds the suspected value compared to gel caps in clinical practice.

D. Conclusion

In conclusion, while more research and clinical trials will be necessary to establish (1) the full benefits of the sponge cap, and (2) under what circumstances it should and should not be used, our data shows that the preparation time of the sponge cap is more than three times shorter compared to that of the gel cap, while the measured cortical responses stay qualitatively comparable in both caps. Sponge EEG caps therefore may offer the solution for the underutilization of low and high-density EEG.

REFERENCES

[1] Doerrfuss, J., Kilic, T., Ahmadi, M., Holtkamp, M. & Weber, J. Quantitative and Qualitative EEG as a Prediction Tool for Outcome and Complications in Acute Stroke Patients. *Clinical EEG And Neuroscience*. **51** pp. 121-129 (2020,3)

[2] Mellish, L., Dunkley, C., Ferrie, C. & Pal, D. Antiepileptic drug treatment of rolandic epilepsy and Panayiotopoulos syndrome: Clinical practice survey and clinical trial feasibility. *Archives Of Disease In Childhood*. **100**, 62-67 (2015,1)

[3] Vlaar, M. Characterizing Cortical Responses Evoked by Robotic Joint Manipulation after Stroke. , *PhD Thesis TU Delft*. https://doi.org/10.4233/uuid:04b4caa3-1d27-4b97-85ff-2036deb70be8 (2017)

[4] Krishnan, A., Kumar, R., Venkatesh, P., Kelly, S., Member, S. & Grover, P. Low-cost Carbon Fiber-based Conductive Silicone Sponge EEG Electrodes. (2018)

[5] Stoyell, S., Wilmskoetter, J., Dobrota, M., Chinappen, D., Bonilha, L., Mintz, M., Brinkmann, B., Herman, S., Peters, J., Vulliemoz, S., Seeck, M., Hämäläinen, M. & Chu, C. High-Density EEG in Current Clinical Practice and Opportunities for the Future. *Journal Of Clinical Neurophysiology*. **38**, 112-123 (2021)

[6] Martens 05.04.029 EEG bij volwassenen en bij kinderen. (Groene Hart Ziekenhuis,2021), www.ghz.nl.

[7] n,A. Maasstad Ziekenhuis. Elektro-encefalogram (EEG). , https://www.maasstadziekenhuis.nl/onderzoeken/elektro-encefalogram-eeg/

[8] n,A. Herseninfarct en hersenbloeding. *Nederlandse Vereniging voor Neurologie* (Richtlijnendatabase,2023)

[9] Filatova, O., Yang, Y., Dewald, J., Tian, R., Maceira-Elvira, P., Takeda, Y., Kwakkel, G., Yamashita, O. & Helm, F. Dynamic Information Flow Based on EEG and Diffusion MRI in Stroke: A Proof-of-Principle Study. *Frontiers In Neural Circuits*. **12** (2018,10)

[10] Erani, F., Zolotova, N., Vanderschelden, B., Khoshab, N., Sarian, H., Nazarzai, L., Wu, J., Chakravarthy, B., Hoonpongsimanont, W., Yu, W., Shahbaba, B., Srinivasan, R. & Cramer, S. Electroencephalography Might Improve Diagnosis of Acute Stroke and Large Vessel Occlusion. *Stroke*. pp. 3361-3365 (2020)

[11] Chu, C. High density EEG-What do we have to lose?. *Clinical Neurophysiology*. **126** pp. 433-434 (2015,3)

[12] Tatum, W., Mani, J., Jin, K., Halford, J., Gloss, D., Fahoum, F., Maillard, L., Mothersill, I. & Beniczky, S. Minimum standards for inpatient long-term video-EEG monitoring: A clinical practice guideline of the international league against epilepsy and international federation of clinical neurophysiology. *Clinical Neurophysiology*. **134** pp. 111-128 (2022,2)

[13] Aghajani, H., Zahedi, E., Jalili, M., Keikhosravi, A. & Vahdat, B. Diagnosis of early Alzheimer's disease based on EEG source localization and a standardized realistic head model. *IEEE Journal Of Biomedical And Health Informatics*. **17**, 1039-1045 (2013)

[14] Lazarou, I., Georgiadis, K., Nikolopoulos, S., Oikonomou, V., Stavropoulos, T., Tsolaki, A., Kompatsiaris, I. & Tsolaki, M. Exploring Network Properties Across Preclinical Stages of Alzheimer's Disease Using a Visual Short-Term Memory and Attention Task with High-Density Electroencephalography: A Brain-Connectome Neurophysiological Study. *Journal Of Alzheimer's Disease*. **87**, 643-664 (2022)

[15] Lascano, A., Lalive, P., Hardmeier, M., Fuhr, P. & Seeck, M. Clinical evoked potentials in neurology: A review of techniques and indications. *Journal Of Neurology, Neurosurgery And Psychiatry*. **88** pp. 688-696 (2017,8)

[16] Fiedler, P., Fonseca, C., Supriyanto, E., Zanow, F. & Haueisen, J. A high-density 256-channel cap for dry electroencephalography. *Human Brain Mapping*. **43**, 1295-1308 (2022,3)

[17] Lin, S., Liu, J., Li, W., Wang, D., Huang, Y., Jia, C., Li, Z., Murtaza, M., Wang, H., Song, J., Liu, Z., Huang, K., Zu, D., Lei, M., Hong, B. & Wu, H. A Flexible, Robust, and Gel-Free Electroencephalogram Electrode for Noninvasive Brain-Computer Interfaces. *Nano Letters*. **19**, 6853-6861 (2019,10)

[18] Kam, J., Griffin, S., Shen, A., Patel, S., Hinrichs, H., Heinze, H., Deouell, L. & Knight, R. Systematic comparison between a wireless EEG system with dry electrodes and a wired EEG system with wet electrodes. *NeuroImage*. **184** pp. 119-129 (2019,1)

[19] Günther, M., Schuster, L., Boßelmann, C., Lerche, H., Ziemann, U., Feil, K. & Marquetand, J. Sponge EEG is equivalent regarding signal quality, but faster than routine EEG. *Clinical Neurophysiology Practice*. (2023,3), https://linkinghub.elsevier.com/retrieve/pii/S2467981X23000045

[20] N.A ANT Neuro — inspiring technology for the human brain. (https://www.ant-neuro.com/), Accessed: 24/05/2023

[21] Ferree, T., Luu, P., Russell, G. & Tucker, D. Scalp electrode impedance, infection risk, and EEG data quality. , www.cdc.gov

[22] Nolan, H., Whelan, R. & Reilly, R. FASTER: Fully Automated Statistical Thresholding for EEG artifact Rejection. *Journal Of Neuroscience Methods*. **192**, 152-162 (2010,9)

[23] Koo, T. & Li, M. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal Of Chiropractic Medicine*. **15**, 155-163 (2016,6)

[24] Kappenman, E. & Luck, S. The effects of electrode impedance on data quality and statistical significance in ERP recordings. *Psychophysiology*. **47**, 888-904 (2010,9)

[25] Pedroni, A., Bahreini, A. & Langer, N. Automagic: Standardized preprocessing of big EEG data. *NeuroImage*. **200** pp. 460-473 (2019,10)

[26] Delorme, A. & Martin, J. Automated Data Cleaning for the Muse EEG. *Proceedings - 2021 IEEE International Conference On Bioinformatics And Biomedicine, BIBM 2021*. pp. 3611-3615 (2021)

V. Appendices

A. *Dataset exclusion based on SNR outlier*

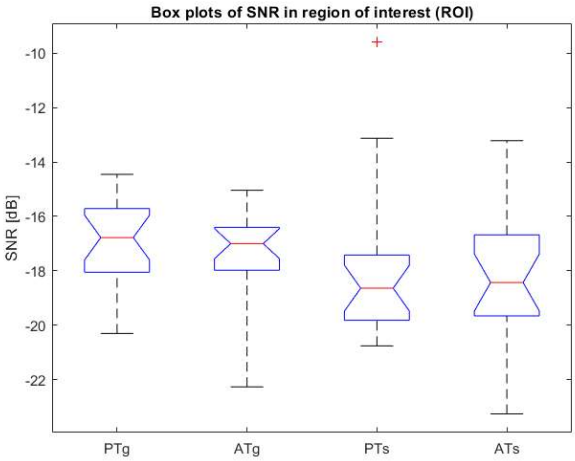

Fig. 12: Box plots of average SNR in ROI; PTg = passive task gel cap, ATg = active task gel cap, PTs = passive task sponge cap, ATs = active task sponge cap.

B. *Electrode layout 10/5 vs equidistant*

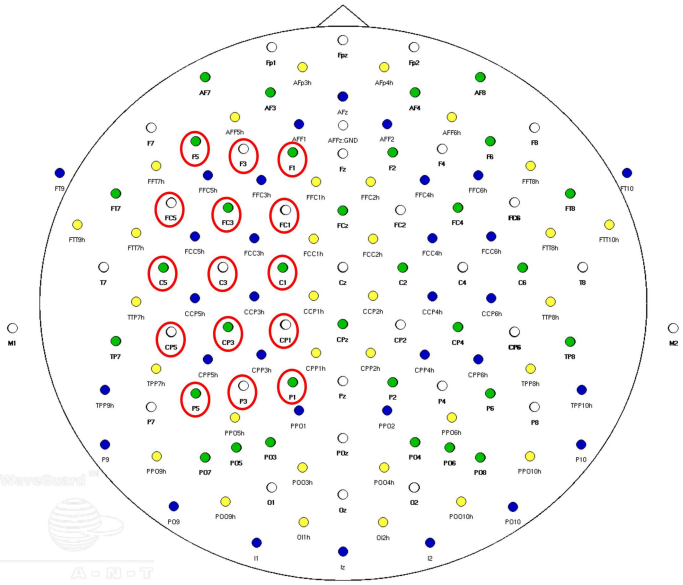

Fig. 13: 10/5 electrode layout. Area of homologous electrodes that were selected as region of interest are marked red.

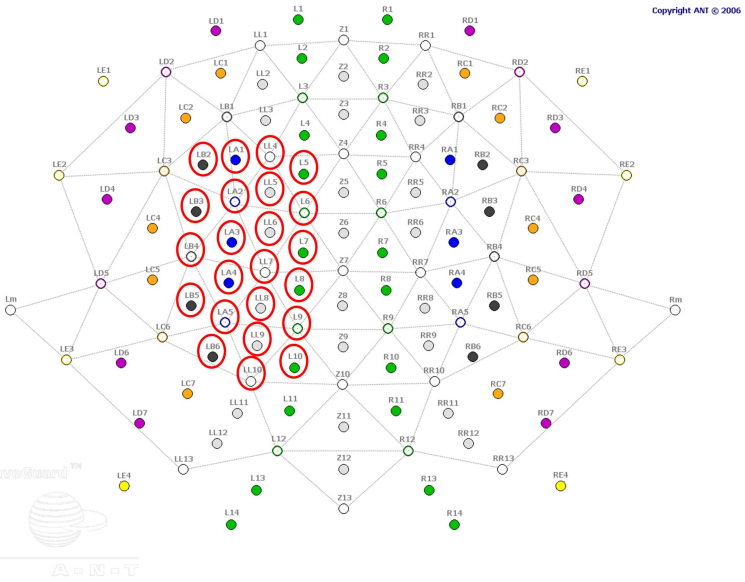

Fig. 14: Equidistant electrode layout. Electrodes that were selected as region of interest are marked red.

C. *Sponge Impedance Threshold Determination*

For the sponge cap, the impedance threshold was set to a relative threshold based on the threshold for the gel cap. First, we calculated the number of standard deviations n that the set threshold of 20kΩ was away from the average impedance of all gel measurements (excluding impedance values of over 500kΩ):

$$n = \frac{\theta_{gel} - \frac{1}{N}\sum_{i=1}^{N} Z_{i,gel}}{\frac{1}{M}\sum_{i=1}^{M} \sigma_{i,gel}} \tag{6}$$

Where n is the number of standard deviations that the average gel impedance is away from 20kΩ, θ_{gel} is the threshold of 20kΩ, N is the total number of gel impedance values (128 channels *20 sessions, excluding values of over 500kΩ), $Z_{i,gel}$ is the i^{th} impedance value, M is the number of gel measurements (20), $\sigma_{i,gel}$ is the standard deviation of the i^{th} measurement. With the calculated n, the threshold for the sponge impedance was calculated (impedance values of over 1000kΩ were excluded):

$$\theta_{sp} = n * \frac{1}{M}\sum_{i=1}^{M} \sigma_{i,sp} + \frac{1}{N}\sum_{i=1}^{N} Z_{i,sp} \tag{7}$$

Where θ_{sp} is the sponge impedance threshold, M is the number of sponge measurements (20), $\sigma_{i,sp}$ is the standard deviation of the i^{th} sponge measurement, N is the total number of impedance values (excluding values of over 1000kΩ), $Z_{i,sp}$ is the i^{th} sponge impedance value.

In sponge measurements with an average impedance higher than θ_{sp}, the threshold was raised to a relative threshold in order to let channels with high impedance still contribute to the EEG cap comparison:

$$\theta_{sp,r} = n * \sigma_{sp,r} + \frac{1}{N_r}\sum_{i=1}^{N_r} Z_{i,sp,r} \tag{8}$$

Where $\theta_{sp,r}$ is the raised sponge impedance threshold for one measurement, $\sigma_{sp,r}$ is the standard deviation of one measurement, N_r is the total number of impedance values of one measurement (excluding values of over 1000kΩ) and $Z_{i,sp,r}$ is the i^{th} sponge impedance value.

D. Relation between impedance and SNR

To investigate the relation between electrode impedance values and SNR values, the mean SNR in the ROI of both caps during the passive task was plotted against the mean impedance in the ROI, and fitted with robust linear regression.

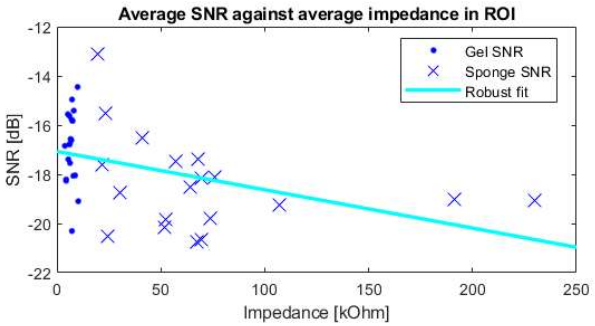

Fig. 15: Average SNR against average impedance in region of interest. R^2 = 0.18, p = 0.01

The relation between average electrode impedance and average SNR in the ROI, is weak (R^2 = -0.18) but statistically significant (p=0.01) (**Figure 15**).