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SENSOR TYING, OPTIMAL MONTAGES FOR VEP-BASED BCI

S. Ahmadi[1], M. Borhanazad [1], D. Tump [2], J. Farquhar [1], P. Desain[1]

[1]Donders Institute for Brain, Cognition and Behaviour, Radboud University, Nijmegen, The Netherlands
[2]MindAffect, Nijmegen, The Netherlands

E-mail: s.ahmadi@donders.ru.nl

ABSTRACT: As Brain computer interfaces (BCI's) attract more attention in the customer market, the need for easy-to-use headsets increases. In this paper we propose an optimized fixed montage EEG headset for VEP BCIs based on covering the most relevant areas on the skull with simulated large sensors. To obtain large sensors, we propose to tie (that is short-circuit) multiple sensors and we simulate the tying by averaging the signals. We show that a circular center-surround configuration with proper sensor tying can provide high performance and good robustness to misplacement of the headset while the number of required channels can be as few as eight. We also provide an alternative cheap design requiring only two channels, which can still achieve acceptable average performance.

INTRODUCTION

Recently, Brain Computer Interfaces (BCIs) have attracted more attention in the general consumer market. Contrary to current BCIs used in a lab setting, with long and precise cap fitting, this new group requires short cap fitting with a robustness against slight displacement [5]. Therefore, there is an increased need for easy-to-use headsets.

One way to make headsets easier to use is with a fixed montage. However, this makes the headset dependent on the type of brain response expected. Visual evoked potential (VEP), especially broad band VEP BCIs (BBVEP) are found to be the fastest BCIs [1], and therefore the most suitable to bring to users. The spatial activity patterns reported for VEP systems clearly show that the brain response is spatially localized to the occipital lobe [2, 7]. The full EEG cap can therefore be replaced with a headset measuring only around the area of interest, reducing the number of channels and simplifying the design. The reduction in number of channels not only reduces amplifier costs, it also reduces computation costs. This is especially important when the BCI systems need to be more compact, such as embedded on a chip, or run on batteries.

One aspect of usability on the consumer market is that the headset needs to be robust to slight misplacement. This would imply that we need to measure the significant signals accurately, even when the EEG sensors might be positioned at slightly different location. One way to achieve this without requiring additional channels is simply to use physically larger EEG sensors spaced further apart. As moving such a large sensor only has a small effect on the measured area of the scalp, the output should be insensitive to misplacement. As large sensors are not commonly available, we suggest to construct such a sensor by electrically tying together multiple sensors into one channel. In this paper, we simulate sensor tying by means of averaging their signals. Under some conditions, like roughly similar impedances, such averaging of individual sensor measurements can be shown, at least to a first approximation, to give a similar result as physical electrical tying [6].

In this paper we develop an optimized fixed montage for VEP BCIs by comparing different montages in a BBVEP visual speller [7]. Montages are evaluated in terms of their accuracy for an average and worse subject. Robustness to misplacement is also evaluated in terms of the worst case drop in accuracy for a given displacement. We conclude by identifying the 'optimal' montage for VEP BCIs which demonstrate reliable performance whilst maximising ease-of-use in a home setting.

MATERIALS AND METHODS

Design ideas: The average spatial filter of the BBVEP speller, found by [7], suggests that the most important areas for decoding during the BBVEP task is a classic Laplician-derivation with circular center-surround shape at the back of the head (Fig.1a). Therefore we propose a circular design, covering the active area with a center-surround configuration, an invention described in [3], with an inner circle and outer ring (Fig.1b). To allow for the fact that not all subjects have an ideal circularly symmetric response, like the one captured by the atypical spatial filter of [7] shown in Fig.1c, we propose different ways of breaking each area into sub-regions (Fig.1d). Thus, to identify the 'optimal' center-surround montage we need to identify the correct size for the center and the ring, the number of sub-regions and the sub-regions shapes.

Experimental setup: Physically making and evaluating all possible montages would require excessive subject recording hours. Thus we evaluated possible mon-

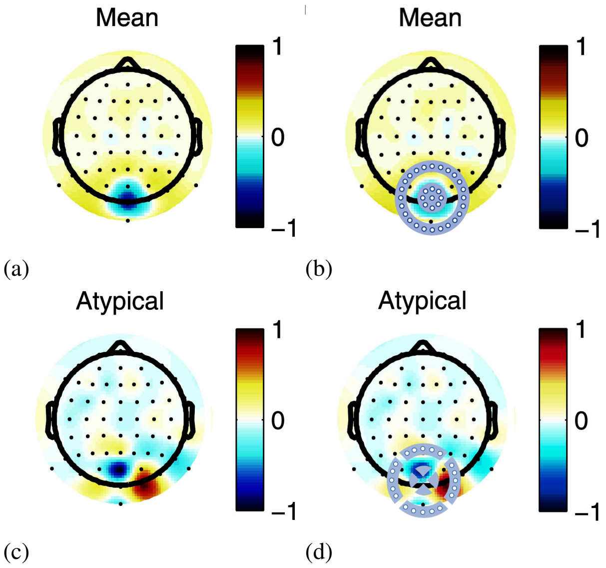


Figure 1: a: The grand average spatial filter of the BBVEP visual speller. (Figure adapted from [7]). b: proposed circle design c: an example of circularly asymmetric spatial filter d: Breaking the circle design to deal with the possible asymmetric spatial response.

tages in off-line simulation by averaging the sensor measurements in each sub-region from an off-line experiment recorded with a high-density EEG system (256 sensors with 20mm sensor spacing).

Participants were seated at a distance of 60 cm from the screen. EEG data was recorded with a 256 Biosemi cap with gel electrodes at a rate of 360 Hz. A Biosemi-active2 amplifier was used and the data was recorded based on a HQ reference system. The BBVEP speller consisted of 3 blocks of 36 trials. In each block the subject was instructed to attend to 36 characters in a random order. The order was different for each training block but the same across subjects. Each trial had a length of 4.2 seconds, with an inter trial time of 0.5 second.

Stimuli: Stimuli consisted of a flickering matrix-layout keyboard presented at 60Hz. All buttons flickered from black to white colors according to a Gold code [4]. The modulated Gold codes ensure small cross-correlations between flickering patterns. The flickering pattern consists of two event types; long and short flashes.

Participants: 5 healthy adults (age: 37.6 ± 16.6, mean ± standard deviation, 1 female) participated in the study after having signed written informed consent. All participants had normal to corrected-to-normal vision and no history of epilepsy. The study was approved by and conducted in accordance with the guidelines of the Ethical Committee of the Faculty of Social Sciences at the Radboud University.

Analysis: To simulate various montages, we consider each individual measuring point on the skull as one sensor, which in our experiment setting is one of the 256 electrodes. To form one channel covering a wider area (consisting of multiple sensors), we tie multiple sensors together by averaging the signals of the sensors.

We apply sensor tying in the circle design in two ways:

1. C-C montage. Two channels comprising of one filled circle in the middle surrounded by another circle (ring) which diameter is between 12.5 to 45 mm larger. Each circle is formed by tying the sensors together into one channel located in the area covered by that circle (Fig.2a).
2. CS-CS montage. One filled circle in the middle divided into 4 segments, surrounded by another circle (ring) which diameter is between 12.5 to 45 mm larger. The second circle is also divided into 4 segments and altogether form 8 channels (Fig. 2b)

The resulting signals after sensor-tying were then fed into our standard BBVEP analysis pipeline, which is given in [7]. See [7] for detailed information, but in outline this consisted of; spectral filtering with a pass band of 2-48Hz followed by model-fitting using CCA to identify subject-specific spatial filters and pulse responses. During testing the pulse responses are re-convolved with the stimulation pattern for each possible output to generate per-output template responses. The predicted target is then identified as the output with maximal correlation between the spatially filtered data and the template response. Accuracy, defined as the percentage of trials where the predicted output was correct, is used in this paper to assess the performance of a montage.

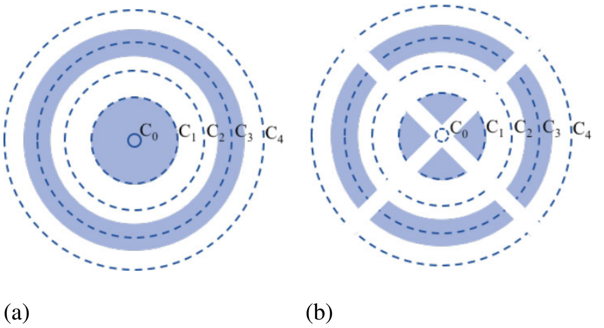
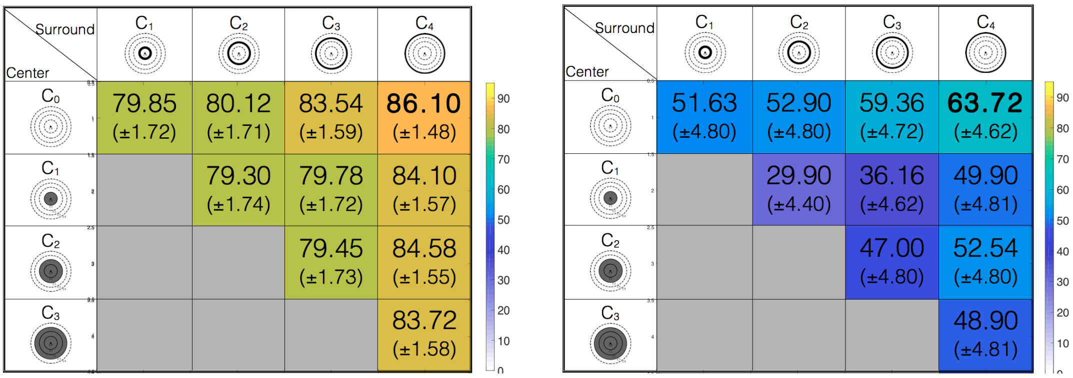


Figure 2: example of a:the C-C montage (C1-C3) and b: CS-CS montage (C1S-C3S). The dashed circles show possible circle sizes.

To study the effect of circle diameter and find the optimum diameter for the inner (center) and outer (surround) circles, we vary the sizes within four values. For the center circle, one of the four following circles is used: C_0 ⌀2mm (a single sensor), C_1 ⌀40mm, C_2 ⌀65mm, C_3 ⌀95mm. Similarly, the surround circle has one of the following four sizes: C_1 ⌀20mm, C_2 ⌀65mm, C_3 ⌀95mm and C_4 ⌀120mm (See Fig.2). The step size in circle diameters is of order of the distance between two adjacent sensors in the Biosemi-256 cap. In the rest of this paper we use these circle names to address various configurations of each montage. For example C_0-C_3 is the 2 channel montage with a single sensor as the center circle and C_3 ⌀95mm as the surround circle. Similarly C_1S-C_3S is the 8 channel montage with C_1 ⌀20mm as center circle and the C_3 ⌀95mm as the surround one.

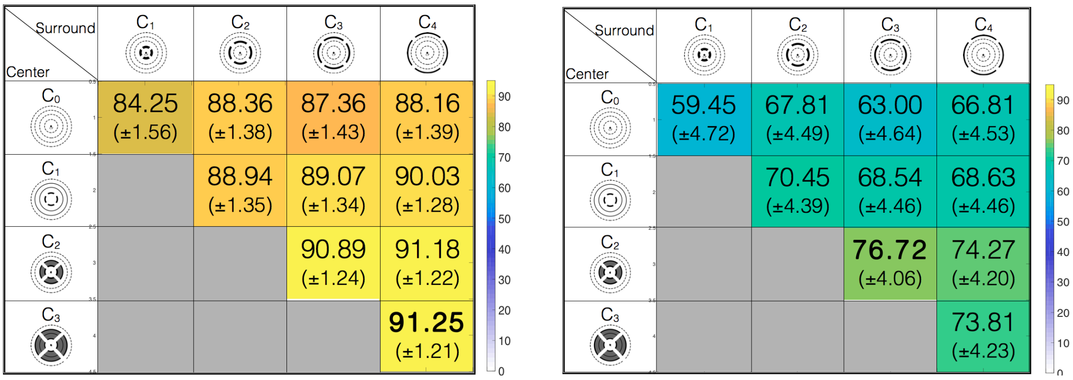


Center \ Surround	C_1	C_2	C_3	C_4
C_0	79.85 (±1.72)	80.12 (±1.71)	83.54 (±1.59)	**86.10** (±1.48)
C_1		79.30 (±1.74)	79.78 (±1.72)	84.10 (±1.57)
C_2			79.45 (±1.73)	84.58 (±1.55)
C_3				83.72 (±1.58)

(a) C-C (2 channels) - Average

Center \ Surround	C_1	C_2	C_3	C_4
C_0	51.63 (±4.80)	52.90 (±4.80)	59.36 (±4.72)	**63.72** (±4.62)
C_1		29.90 (±4.40)	36.16 (±4.62)	49.90 (±4.81)
C_2			47.00 (±4.80)	52.54 (±4.80)
C_3				48.90 (±4.81)

(b) C-C (2 channels) - Worst subject



Center \ Surround	C_1	C_2	C_3	C_4
C_0	84.25 (±1.56)	88.36 (±1.38)	87.36 (±1.43)	88.16 (±1.39)
C_1		88.94 (±1.35)	89.07 (±1.34)	90.03 (±1.28)
C_2			90.89 (±1.24)	91.18 (±1.22)
C_3				**91.25** (±1.21)

(c) CS-CS (8 channels) - Average

Center \ Surround	C_1	C_2	C_3	C_4
C_0	59.45 (±4.72)	67.81 (±4.49)	63.00 (±4.64)	66.81 (±4.53)
C_1		70.45 (±4.39)	68.54 (±4.46)	68.63 (±4.46)
C_2			**76.72** (±4.06)	74.27 (±4.20)
C_3				73.81 (±4.23)

(d) CS-CS (8 channels) - Worst subject

Figure 3: Average and worst performance obtained by simulating the two center configurations with varying center and surround circles. (The numbers in brackets are the 95% confidence interval)

Furthermore, effects of slight displacement of a headset are simulated by choosing different center points. We shifted the center point by two steps horizontally and two steps vertically. Each step size was almost 20mm (one sensor on the cap). The simulation was repeated for each center point by tying the sensors that would be covered by the circles centered at that position. We take the maximum performance drop after 20mm shift as the indicator of the sensitivity to misplacement.

For the analysis presented here 1 second trials are used to avoid saturation effects where all subjects hit perfect performance, and hence increase sensitivity to changes in the montage.

RESULTS

We report the average classification accuracy as well as the accuracy of the worst subject. The worst subject is included to show how each configuration works in a challenging condition.

Figure3 shows the average and worst accuracy, as the percentage of correctly typed characters, for the C-C and CS-CS montages for all the possible center and surround configurations. The numbers in brackets show the 95% confidence interval.

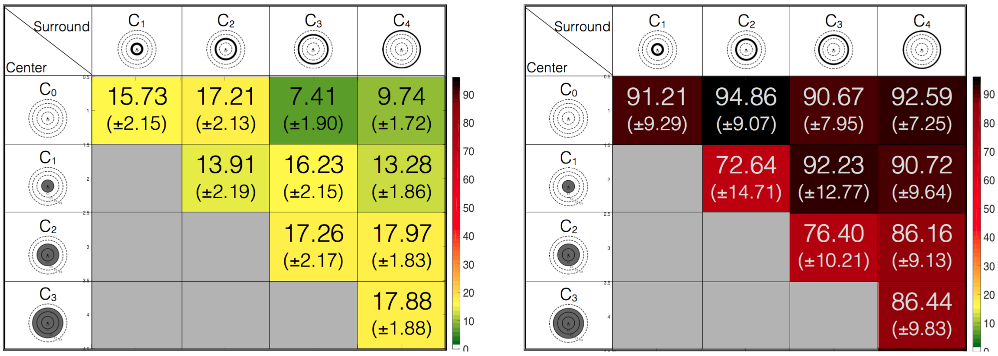
In Fig.4 The maximum relative performance drop as a result of moving the central point by 20mm is visualized for all the configurations of both C-C and CS-CS montages.

DISCUSSION

As can be seen in Fig.3a and 3b, increasing the surrounding circle in size in the C-C montage results in a higher performance. Increasing the size of the center circle only decreases the performance. For the CS-CS montage however, as Fig.3c and 3d indicate, an increase of the center circle size increases the performance. Moreover, the performance increase as a result of larger surround circle is less compared to the C-C montage. In this case, both 95mm and 120mm surround circles give similar high performance (to within the 95% confidence intervals).

According to Fig.3a and 3b, the best C-C two channel configuration in terms of average and worst performance is when the configuration has a single point center with a 120mm surrounding circle (C_0-C_4).

The 8 channel configuration (CS-CS montage) as can be seen in Fig.3c and 3d, shows higher performances with maxima reached at 95mm center circle and 120mm surround circle (C_3S-C_4S) for average performance and at 65mm center circle and 95mm surround circle (C_2S-C_3S) for the worst subject. The difference in performance, however, between the 65mm and 95mm center circle and 95mm and 120mm surround circle is not statistically significant. The average accuracy obtained using the full 256 channels was 92.49±1.21%. Clearly, the difference between the performance of our optimal CS-CS montage (C_3S-C_4S) and the full cap is insignificant. The same

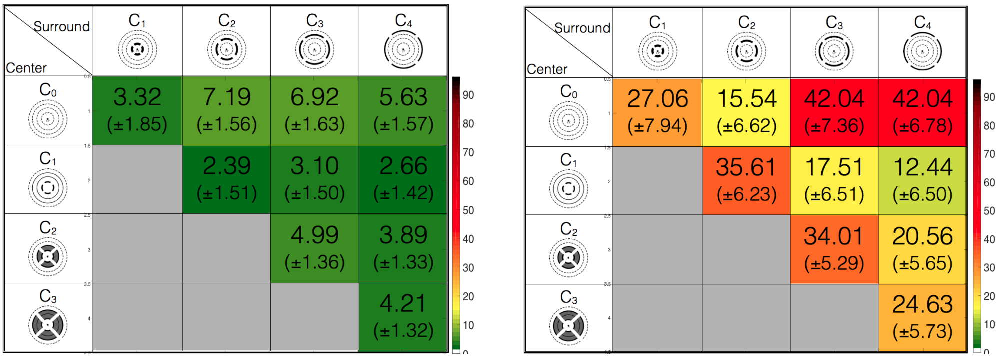


(a) C-C (2 channels) - Average

Center \ Surround	C_1	C_2	C_3	C_4
C_0	15.73 (±2.15)	17.21 (±2.13)	7.41 (±1.90)	9.74 (±1.72)
C_1		13.91 (±2.19)	16.23 (±2.15)	13.28 (±1.86)
C_2			17.26 (±2.17)	17.97 (±1.83)
C_3				17.88 (±1.88)

(b) C-C (2 channels) - Worst subject

Center \ Surround	C_1	C_2	C_3	C_4
C_0	91.21 (±9.29)	94.86 (±9.07)	90.67 (±7.95)	92.59 (±7.25)
C_1		72.64 (±14.71)	92.23 (±12.77)	90.72 (±9.64)
C_2			76.40 (±10.21)	86.16 (±9.13)
C_3				86.44 (±9.83)



(c) CS-CS (8 channels) - Average

Center \ Surround	C_1	C_2	C_3	C_4
C_0	3.32 (±1.85)	7.19 (±1.56)	6.92 (±1.63)	5.63 (±1.57)
C_1		2.39 (±1.51)	3.10 (±1.50)	2.66 (±1.42)
C_2			4.99 (±1.36)	3.89 (±1.33)
C_3				4.21 (±1.32)

(d) CS-CS (8 channels) - Worst subject

Center \ Surround	C_1	C_2	C_3	C_4
C_0	27.06 (±7.94)	15.54 (±6.62)	42.04 (±7.36)	42.04 (±6.78)
C_1		35.61 (±6.23)	17.51 (±6.51)	12.44 (±6.50)
C_2			34.01 (±5.29)	20.56 (±5.65)
C_3				24.63 (±5.73)

Figure 4: % Relative drop in average and worst subject accuracy as a result of 20mm shift of the central point for both C-C and CS-CS montages (The numbers in brackets are the 95% confidence interval).

holds for the worst subjects performance (78.54±3.95% obtained by the full cap compared to 76.72±4.06%) of the C_2S-C_3S montage

It is clear that the 8 channel configuration is superior to the 2 channel one, especially for the bad subject. However, the average performance of the 2 channel configuration is good enough to make such a montage an attractive option for making a cheap EEG headset.

The difference between the 2 channel C-C montage and the 8 channel CS-CS one becomes more visible by looking at the sensitivity of each montage to misplacement. Fig.4 shows the percentage drop in accuracy as the center point of each montage moves 20mm away from the ideal point. The drop reported is the maximum drop in performance of the four possible displacement directions. Comparing Fig.4a and 4c shows that the CS-CS montage is overall less sensitive to misplacement (2.4% up to 7.2% relative drop in performance depending on the circle sizes, compared to 7.4% up to 17.97% of the C-C montage). While the results in Fig.3c indicate that the best center size for achieving maximum average performance of the CS-CS montage is 95mm (C_3), according to Fig.4c, there seem to be a slight preference for a 40mm center circle (C_1) in terms of robustness to misplacement, however, this difference is not statistically significant. According to Fig.3a, the best result of the C-C montage is obtained when there is a single electrode inner-circle (C_0) with a far outer circle. However, this effect is strongly caused by the worst subject. Moreover, in terms of robustness to misplacement, in this case, the 95mm surround circle (C_3) has a slight advantage to the 120mm one.

As illustrated in Fig.4b, the performance of the C-C montage for the worst subject can drop dramatically by shifting the headset 20mm to the side. However, the CS-CS montage seem to handle such a condition very well (Fig.4d). This can be an example of a circularly asymmetric response due to a non-radial dipole (see Fig1c). In this case, having very large sensors increases the chance that a single sensor is placed across the boundary between the positive and negative components and averages the signals that need to be kept separate for detection. This can also explain why the best C-C configuration for the worst subject is the one with a single point sensor in the center. By splitting the channels, the risk of cancelling out the activities reduces and therefore the placement of the sensors become less difficult. Hence, in this type of design, on one hand large sensors are desirable since they save the number of required channels and on the other hand the sensor should not be too large to mix up different activities and cancel them out. The 8 channel CS-CS montage seem to provide a good trade off.

In short, the 8 channel CS-CS montage seems to provide a higher average accuracy than the 2 channel C-C montage. Importantly for a subject with poor performance, the difference between the CS-CS and C-C montage is even larger. An further advantage of the 8 channel CS-CS montage is that it is relatively robust against misplacement. This robustness increases the usability of a headset for a consumer. The only disadvantage is the increase in channel count and associated costs.

In this paper, sensor tying is defined as an offline averaging over the individual signals of the separate electrodes. In future work we will validate the reliability of this off-line simulation by performing further measurements for the identified best-performing montages with physical sensor tying in an on-line test. This research does, however, show the possible benefits of sensor tying. The robustness against slight displacement, together with a reduction in the number of channels, would make a headset more suitable for home users.

CONCLUSION

In this paper we proposed a fixed montage EEG acquisition headset idea for VEP-based BCI with a focus on home-use customer product design. Our idea was based on covering the most important areas of the skull with a few large sensors in an optimal layout. To evaluate the idea, we did a high density EEG recording and averaged signals from the multiple adjacent sensors to simulate larger sensors in various layouts. We concluded that an 8 channel circular center-surround montage with center size of 95 and surround size of 120mm, results in maximum average classification accuracy which is almost identical to what can be achieved using the full high density measurements. Such a design also provides very good robustness to misplacement such that moving it by 20mm causes only 4% relative drop in performance. The design is also very robust for subjects with asymmetric spatial responses. We also showed that it is possible to reduce the number of channels to 2 and still have acceptable average performance. Even though the placement of such a headset has to be more accurate, it still makes an attractive design for low budget devices.

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