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Common Average Reference (CAR) Improves P300 Speller

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ABSTRACT

In this paper a comprehensive comparative study of the different re-reference techniques are given, as well as, their applications for p300 speller, of both offline and online applications. Twelve different re-reference techniques were applied to three different datasets. Their results were compared with each other. The results showed that Common Average Reference (CAR) is best suited to be the reference technique.

Keywords: *EEG, P300, Common Average Reference, Classification, Montaging, Re-reference, Brain Computer Interface BCI*

1. INTRODUCTION

One of the major problems in EEG recording is to find a region in the human body whose bio-potential activity can be considered as neutral as possible. Ideally, the voltage readings should represent a pure measure of activity at the recording site. The difficulty is that voltage is a relative measure that necessarily compares the recording site with another – reference- site. If there is any activity at the reference site, this will contribute equally to the resulting voltage recording [3]. According to this, Nowadays, it is well known that it is impossible to find a "zero-potential" site on the human body [8]. The most common way of performing EEG recordings is by using as a common reference (CR) an electrode placed somewhere on the head. Starting from this Common Reference, several other re-reference technique or montages can be constructed for interpretation or processing purposes [5]. There are several different recording reference electrode placements such as vertex (Cz), linked-ears, linked-mastoids, ipsilateral-ear, contralateral-ear, C7 reference, bipolar references, and tip of the nose. Reference-free techniques are represented by common average reference, weighted average reference, and source derivation. Each technique has its own set of advantages and disadvantages. The choice of reference may produce topographic distortion if relatively electrically neutral area is not employed. Linking reference electrodes from two earlobes or mastoids reduces the likelihood of artificially inflating activity in one hemisphere. Nevertheless, the use of this method may drift away "effective" reference from the midline plane if the electrical resistance at each electrode differs. Cz reference is advantageous when it is located in the middle among active electrodes, however for close points it makes poor resolution. Reference-free techniques do not suffer from problems associated with an actual physical reference [4].

CAR has been proposed as a method for providing an inactive reference. The underlying principle is that electrical events produce both positive and negative poles. The integral of these potential fields in a conducting sphere sums to exactly zero [3].

In previous studies, McFarland et al. (1997) discussed the selection of spatial filter for EEG-based communication. The Comparison were among standard ear-reference, (CAR), small Laplacian and a large Laplacian . CAR and large Laplacian methods proved best able to distinguish between top and bottom targets [6]. Another study with other results was performed by Ng and Raveendran (2007). According to that study CAR produced poor results, since only the channels over the motor cortex region were considered [2]. Both studies were on motor imagery paradigm.

In P300 paradigm, channel referencing were discussed by Krusienski et al (2008), they conclude that there is no significant difference between CAR and ear-reference, and this is true only in the case of selecting best channels subset [7].

A solution to the reference problem proposed by Hu et al. consists in identifying the reference signal by constraining the Blind Source Separation (BSS) model to particular mixing system which implies that the non-zero reference signal is independent from all other measures. This approach is based on the hypothesis that the reference electrode placed on the scalp is not influenced by the intracranial measures. If for intra-cranial measures this hypothesis (although not proven) can be employed, in a cephalic referenced scalp EEG context it cannot hold, as the reference electrode itself records a noisy mixture of cerebral and extra-cerebral sources [5]. Improvements of this work with more accurate and generalized model were done by R. Salido-Ruiz et al (2010) but still have the same problem.

Still that reference technique has engendered ongoing debate [3]. And they need more and more practical experiments.

Improving the reference technique will positively affect all of the Brain Computer Interface BCI research and P300 is not an exception.

2. RE-REFERENCE METHODS

Montaging or re-reference methods are used to enhance the signal to noise ratio SNR. Twelve different montage methods have been tested, most of them were used by [2] in motor imagery paradigm.

- Common Reference: No re-montaging is done

- Common average reference: The mean of all the electrodes is removed for all the electrodes.

E.g.Cz CAR=Cz-(Fp1+AF3+F7+…+Fz+MA1+MA2)/34

- Surface Laplacian (4 adjacent): The weighted mean (depends on the distance) of the 4 adjacent electrodes is removed from the central electrode.

E.g. CzSL4=Cz-0.7(FC1+ FC2+ CP1+CP2)/4

- Surface Laplacian (8 adjacent): The weighted mean (depends on the distance) of the 8 surrounding electrodes is removed from the central electrode.

E.g. CzSL8=Cz-[0.7(FC1+FC2+CP1+CP2)+0.5(Fz+Pz+ C3+C4)]/4

- Bipolar (front to back): The difference of an electrode with the one behind it.

E.g. CzBFB= Cz-Pz

- Bipolar (front to back skip 1): The difference of 2 electrodes that lies in front and also behind that electrode.

E.g. CzBS1= Cz-Oz

- Bipolar (Symmetrical): The difference of 2 electrodes that is symmetrical to one another.

E.g. C3SYM= C3-C4

- Bipolar (left to right): The difference of an electrode with the one right to it.

E.g. C3LR= C3-Cz

- Bipolar (right to left): The difference of an electrode with the one left to it.

E.g. CzRL= Cz-C3

- Using T7, T8 channels: The mean of T7, T8 channels is removed for all the electrodes.

*E.g.Cz*T7T8=*Cz-(T7+T8)/2*

- Common average reference without mastoid channels: The mean of all the electrodes without mastoid channels is removed for all the electrodes.

E.g.Cz CAR=Cz-(Fp1+AF3+F7+……+Fp2+Fz+AF4)/32

- Reference estimation: Here we apply the work of *R. Ranta et al.* [8] by the estimation of the reference ˆ*r*,

E.g.Cz est = Cz +ˆr

3. APPLICATION OF RE-REFERENCE TECHNIQUES TO THE P300 SPELLER

The previous 12 techniques were applied to 3 different datasets for different subjects:

- Dataset 1: P300 dataset provided by Hoffmann et al. [1].

- Dataset 2: P300 dataset from the BCI competition 2003.

- Dataset 3: P300 dataset obtained from our BCI Lab at KAU hospital. The data were recorded using gUSBamp amplifier and digitized at 256 Hz with 8 electrodes.

Table 1. Comparison between the three datasets

	Dataset 1	Dataset 2	Dataset 3
Sampling rate	2048Hz	240Hz	256Hz
Subjects Number	8	2	1
Filtering	1.0Hz-12.0Hz	0.1Hz-60.0Hz	0.1-60.0Hz
Electrodes no.	32	64	8
Electrodes Locations	Fp1, AF3, F7, F3, FC1, FC5, T7, C3, CP1, CP5, P7, P3, Pz, PO3, O1, Oz, O2, PO4, P4, P8, CP6, CP2, C4, T8, FC6, FC2, F4, F8, AF4, Fp2, Fz, and Cz	FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, C6, Cp5, Cp3, Cp1, Cpz, Cp2, Cp4, Cp6, Fp1, Fpz, Fp2, AF7, AF3, AFz, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, Ft7, Ft8, T7, T8, T9, T10, Tp7, Tp8, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, and Iz	F3, F4, T7, C3, Cz, C4, T8, and Pz

3.1 Dataset 1

The techniques were first applied to Dataset 1, and we found that CAR gives best classification accuracy. Comparison based on classification accuracy between CAR and T7,T8 methods is shown in Fig.1. This accuracy is obtained with Bayesian Linear Discriminant Analysis (BLDA), averaged over all subjects and sessions, plotted against time, for all electrode configurations. According to the accuracy achieved in Fig.1 its clear that CAR outperforms T7, T8 method.

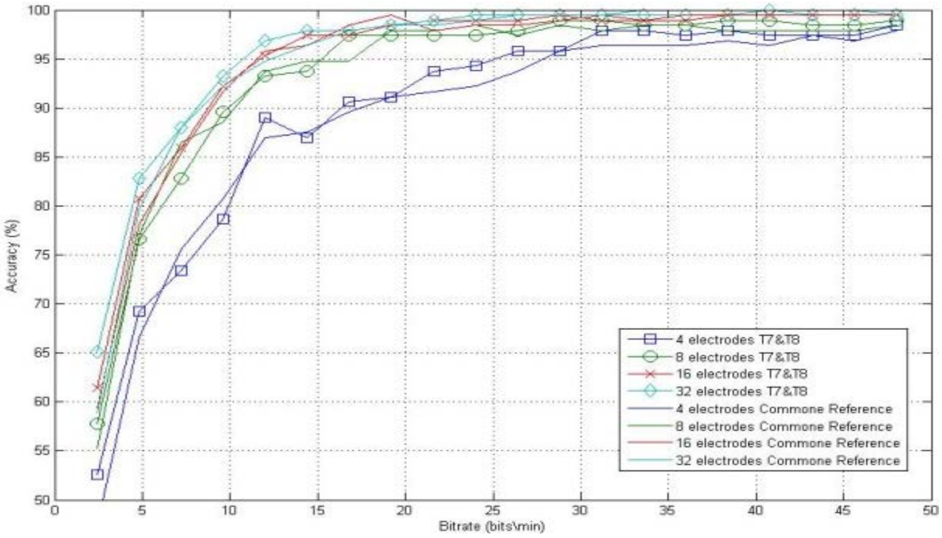
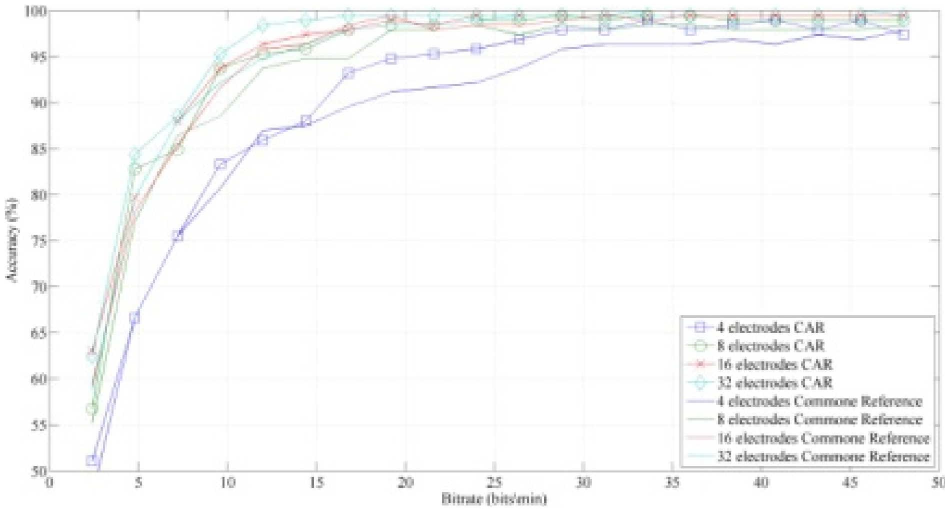


Figure1. T7, T8 & CAR comparison based on classification accuracy, for electrode configurations (4,8,16 and 32)

Comparison based on classification accuracy of other methods - mentioned in section 2- can be found in Fig.2.



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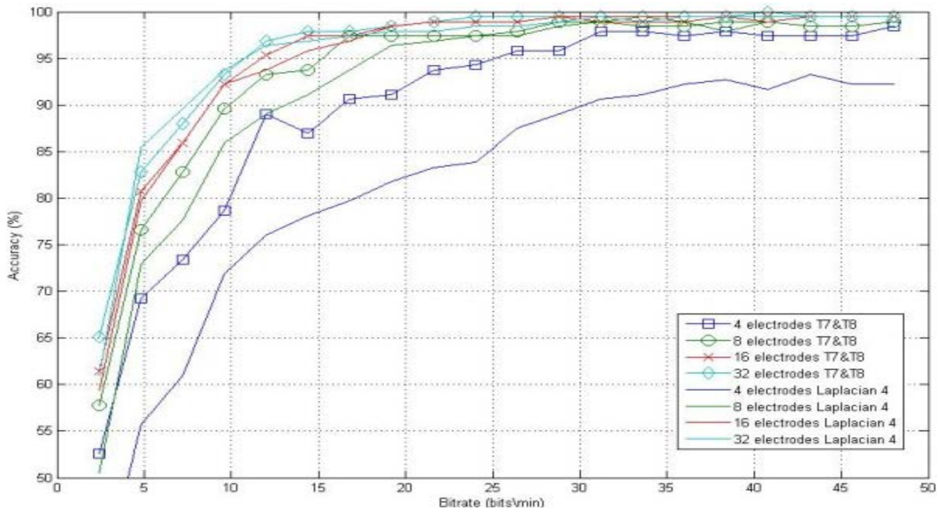

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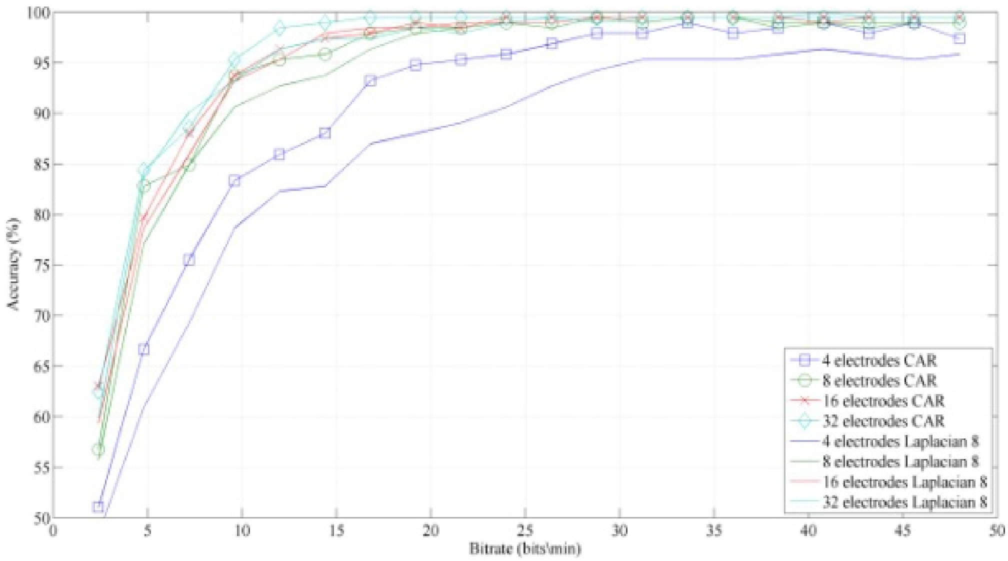

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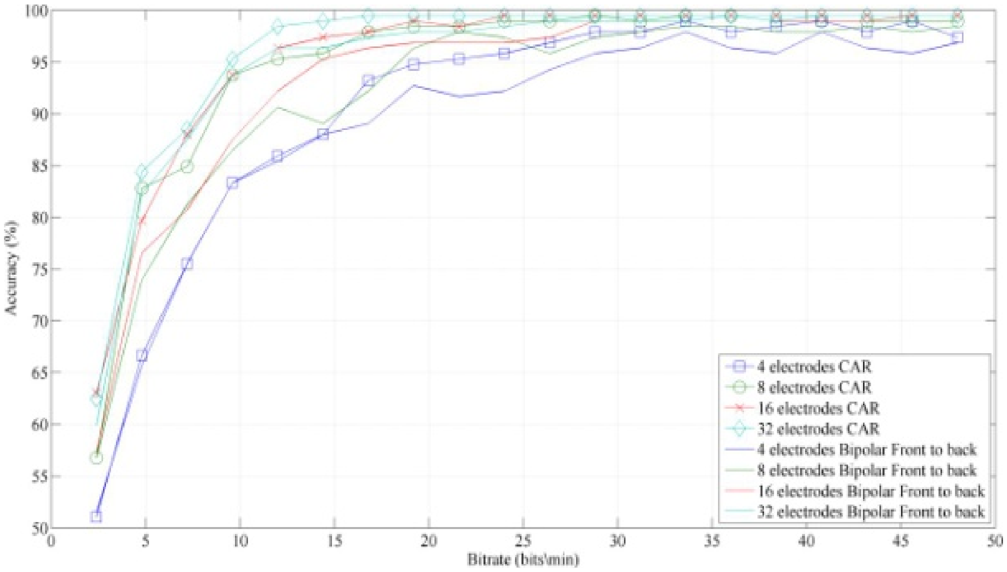
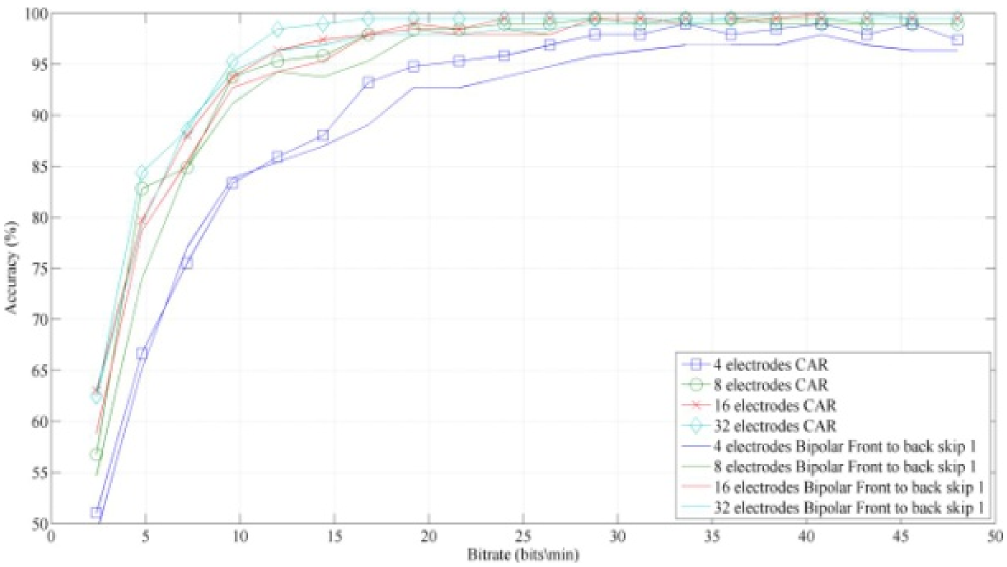
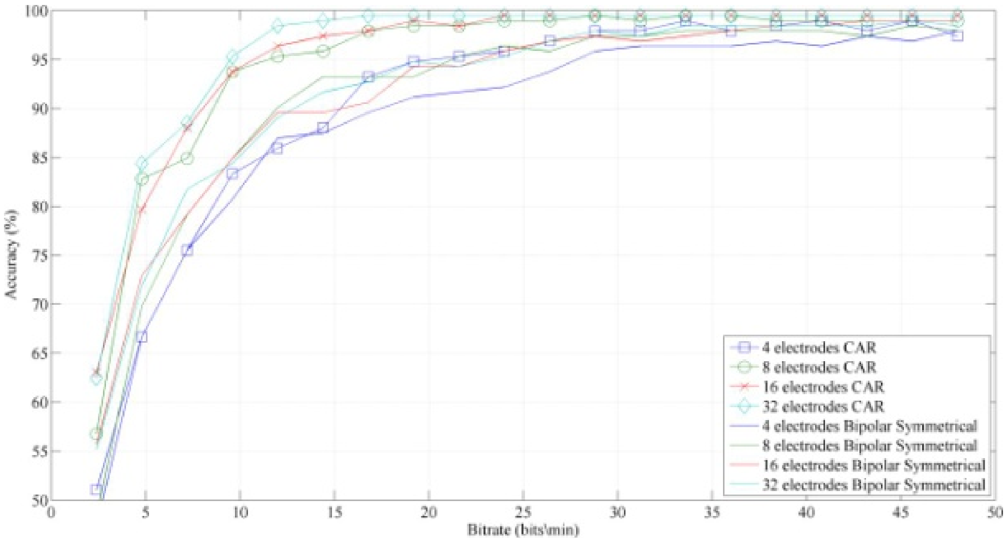

Accuracy (%)
Bitrate (bits\min)
4 electrodes CAR
8 electrodes CAR
16 electrodes CAR
32 electrodes CAR
4 electrodes Bipolar Front to back
8 electrodes Bipolar Front to back
16 electrodes Bipolar Front to back
32 electrodes Bipolar Front to back

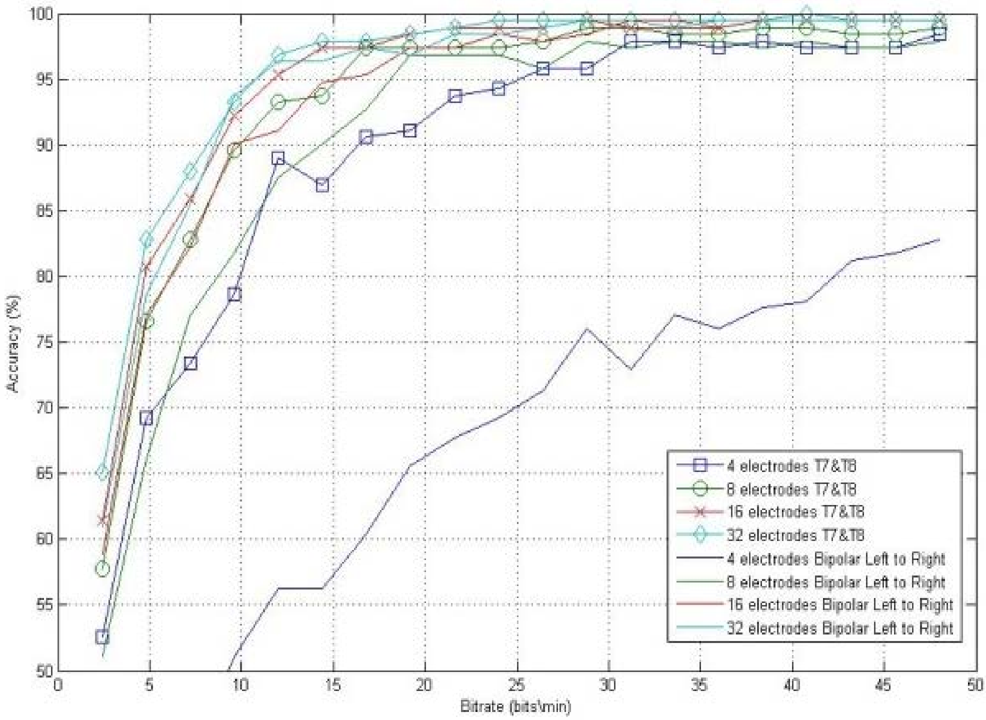
D


Accuracy (%)
Bitrate (bits\min)
4 electrodes CAR
8 electrodes CAR
16 electrodes CAR
32 electrodes CAR
4 electrodes Bipolar Front to back skip 1
8 electrodes Bipolar Front to back skip 1
16 electrodes Bipolar Front to back skip 1
32 electrodes Bipolar Front to back skip 1

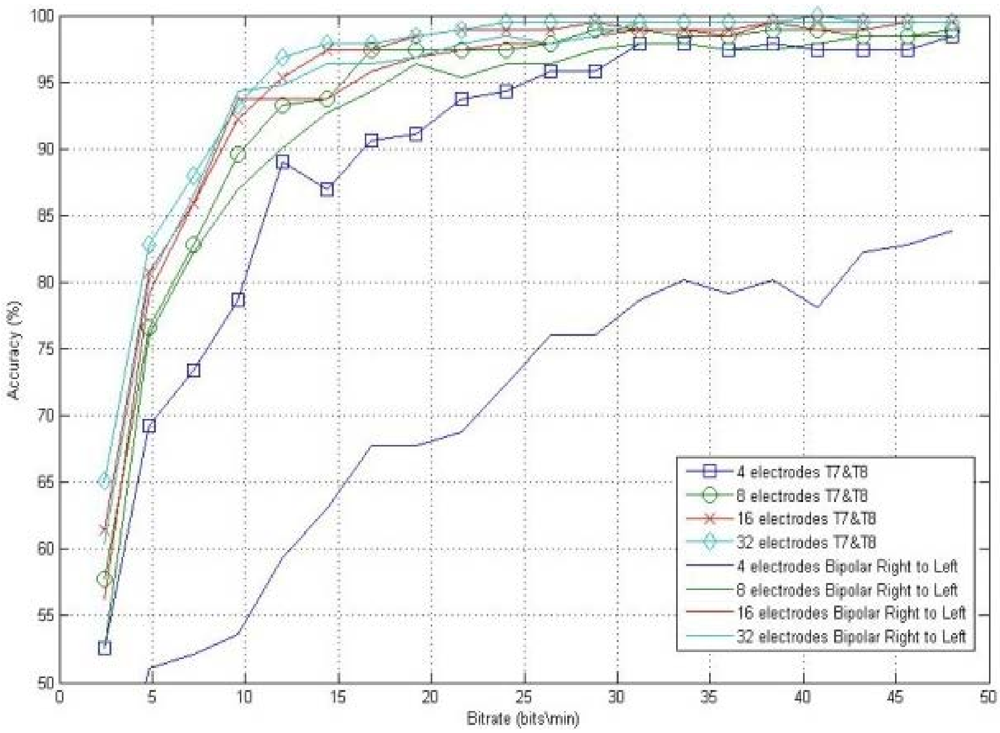
E


Accuracy (%)
Bitrate (bits\min)
4 electrodes CAR
8 electrodes CAR
16 electrodes CAR
32 electrodes CAR
4 electrodes Bipolar Symmetrical
8 electrodes Bipolar Symmetrical
16 electrodes Bipolar Symmetrical
32 electrodes Bipolar Symmetrical

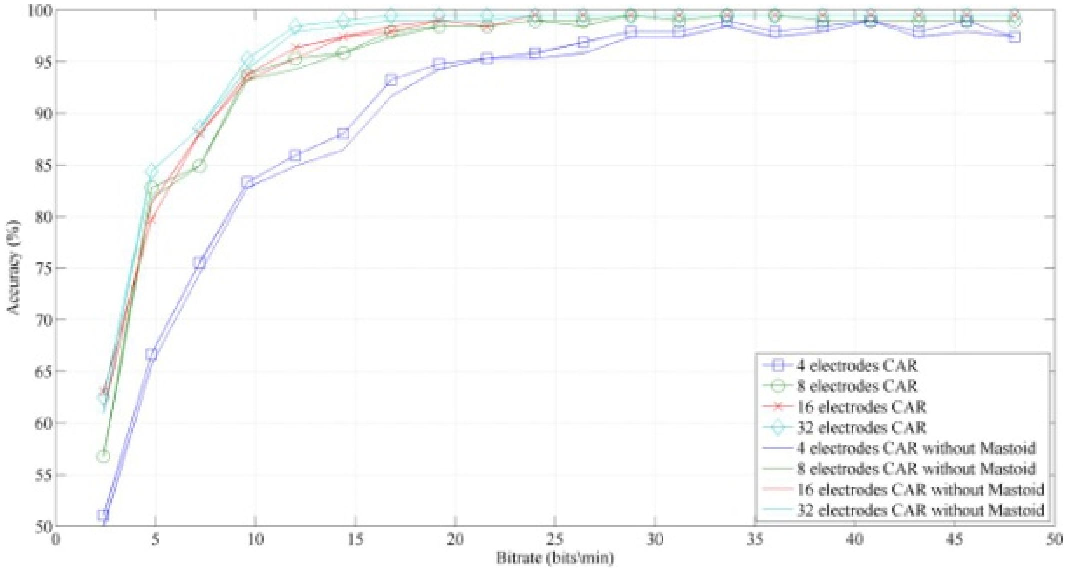
F


Accuracy (%)
Bitrate (bits\min)
4 electrodes T7&T8
8 electrodes T7&T8
16 electrodes T7&T8
32 electrodes T7&T8
4 electrodes Bipolar Left to Right
8 electrodes Bipolar Left to Right
16 electrodes Bipolar Left to Right
32 electrodes Bipolar Left to Right

G


Accuracy (%)
Bitrate (bits\min)
4 electrodes T7&T8
8 electrodes T7&T8
16 electrodes T7&T8
32 electrodes T7&T8
4 electrodes Bipolar Right to Left
8 electrodes Bipolar Right to Left
16 electrodes Bipolar Right to Left
32 electrodes Bipolar Right to Left

H



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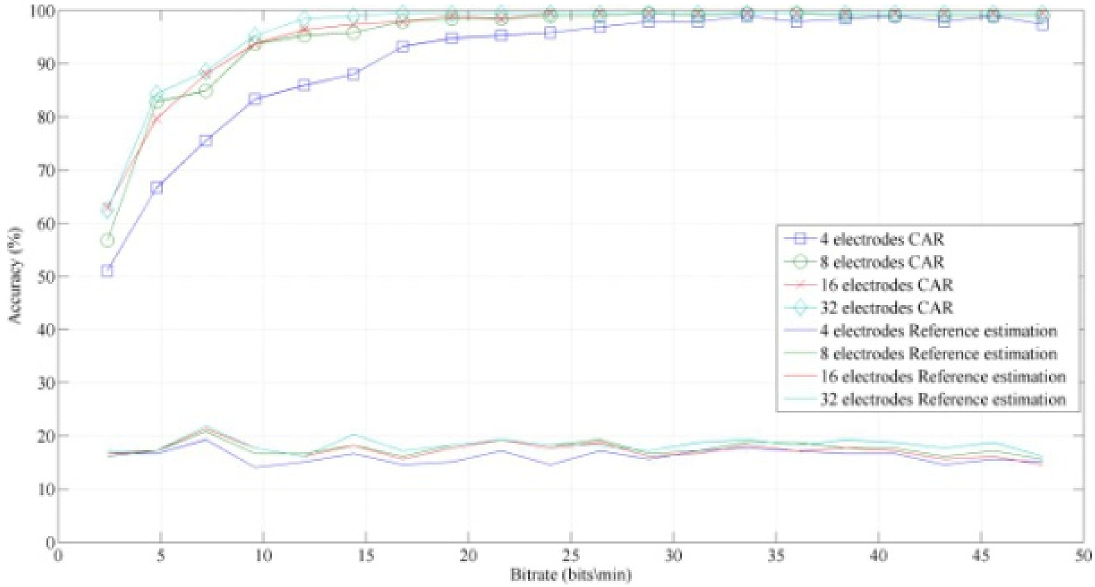


J

Figure 1. Comparison between the different re-reference methods based on classification accuracy, for electrode configurations (4, 8, 16 and 32), obtained with BLDA, averaged over all subjects and sessions, plotted against time, (A) Common Reference, (B) Laplacian 4, (C) Laplacian 8, (D) Bipolar Front to back, (E) Bipolar Front to back skip 1,(F) Bipolar Symmetrical, (G) Bipolar Left to Right, (H) Bipolar Right to Left, (I) CAR without Mastoid, (J) Reference estimation.

Figure 2. shown the comparison between CAR and the different re-reference methods based on classification accuracy. In Fig 2.A, the CAR illustrates slightly better than Common Reference, whereas in Fig 2.B clear deference between CAR and Surface Laplacian with 4 & 8 adjacent electrodes and this is due the small number of electrodes has been used, nevertheless, Fig 2.C demonstrates Laplacian method but not as good as CAR. However, In Bipolar techniques we have five methods which are front to back as shown in Fig2.D, front to back skip 1 in Fig2.E, Symmetrical in Fig2.F, left to right in Fig2.G and, right to left in Fig2.H, it obvious that left to right and right to left are the worst among the five methods, in the other hand we can find that front to back skip 1 gives the best; but again not as good as CAR.

Fig2.I illustrates CAR method but without mastoid electrodes, and we can find the effect of removing such electrodes on the accuracy. Finally, reference estimation method Fig2.J provides poor results and this support the hypothesis that the reference electrode is a noisy mixture of cerebral and extra-cerebral sources, so it is dependent on the other electrodes, which conflict with the BSS model assumption.

3.2 Dataset 2

After that we again applied the techniques to Dataset 2, and the result where compared to each other using Correlation Coefficients method. Where the ensample average is taken over number of trials and correlation coefficients are calculated regarding the whole p300 ensample average. And as shown in Fig.3 that CAR was the pest method.

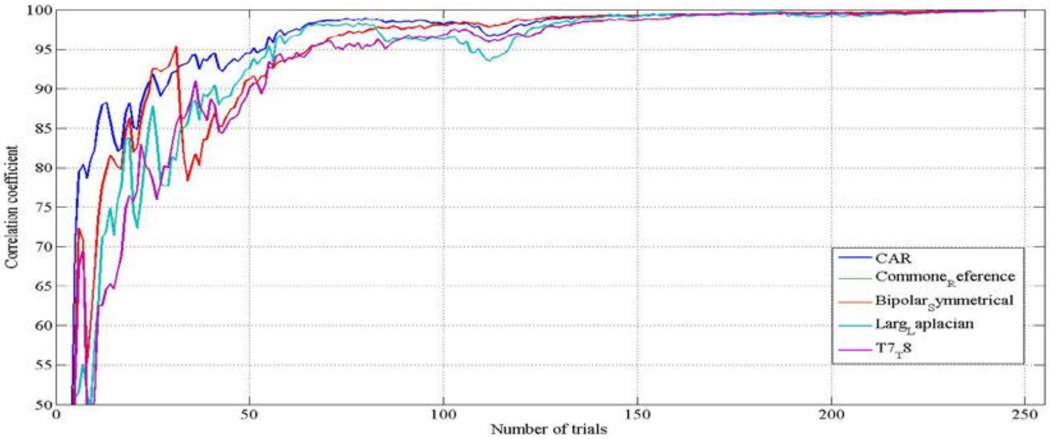


Figure 3. Correlation coefficients with whole p300 ensample average VS Number of trials

3.3 Dataset 3

Finally we applied CAR in Dataset 3, and we found that the accuracy is improved when we use CAR as a rereference technique. In Fig.4 we can see a comparison based on classification accuracy between CAR and CR (right ear lobe) methods.

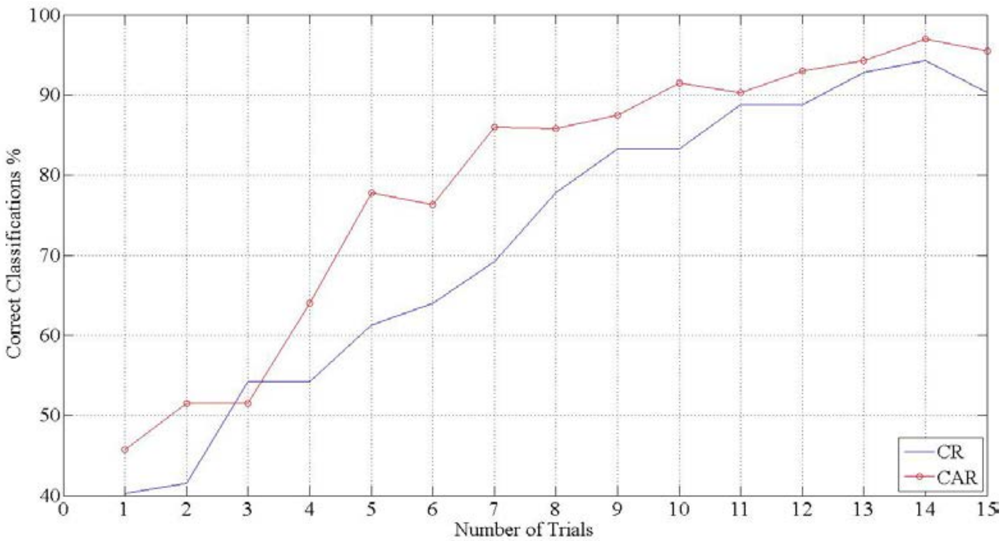
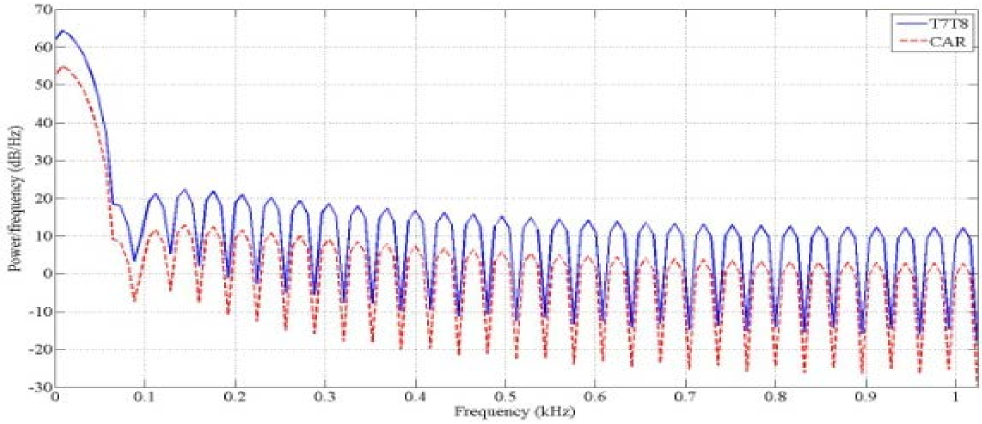


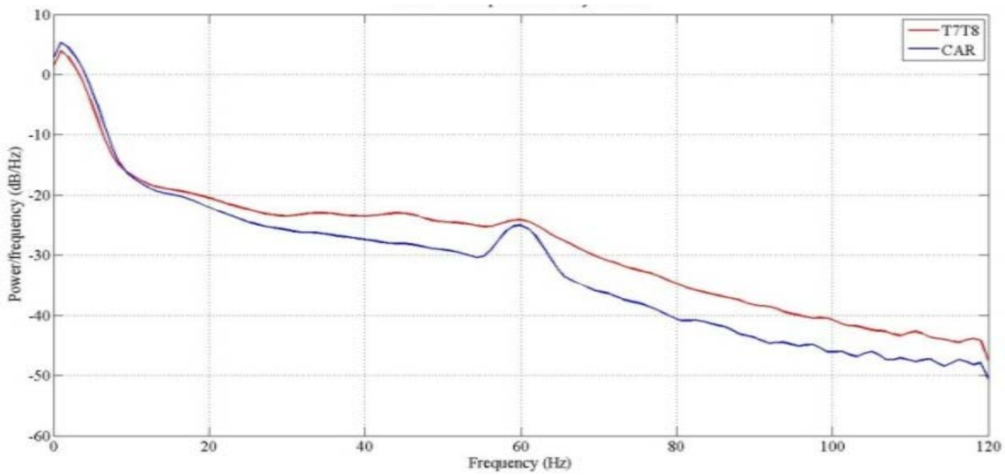
Figure 4. CR & CAR comparison based on classification accuracy

4. DISCUSSION

Based on the results we can see that CAR outperforms other re-reference methods. This can be explained with the concept of the ideal reference, where its activity is as neutral as possible. To measure the naturally we use the Power Spectral Density (PSD). As we can see in Fig.5-A,B that the PSD for CAR is lower than other methods.



A



B

Figure 5. Comparing PSD for CAR & T7T8 methods, for datasets 1 & 2.

in the Appendix section, Table 2,3,4 and 5 shown the Comparison based on Maximum average bitrate per minute obtained with BLDA, averaged over all subjects and sessions, for (4, 8, 16and 32 channels electrode) respectively.

5. CONCLUSION

This paper illustrates that the common average reference (CAR) outperforms the other re-references techniques. The cost of the good performance of the CAR is the increasing of the number of electrodes, in such a way, to be uniformly distributed along the head. The experimental results comply with the mathematical justification of the best performance of the CAR as given in [11].

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APPENDIX

Table 2. Comparison based on Maximum average bitrate per minute obtained with BLDA, averaged over all subjects and sessions, for 4 channels electrode configuration

Subject	S1	S2	S3	S4	S6	S7	S8	S9	Average(S1-S4)	Average(S6-S9)	Average(all)
T7 & T8	9	7	22	15	26	22	39	17	13.1+-6.8	26+-9.2	19.5+-10.2
CAR	7	8	25	13	30	16	34	11	13.2+-8.1	22.8+-10.9	18+-10.3
Common Reference	8	7	15	11	22	22	34	9.5	9.9+-3.6	22.1+-10	16+-9.5
Laplacian 4	6	6	8	8.3	9.5	13	22	7.5	7+-1.3	13.1+-6.6	10+-5.5
Laplacian 8	6	6	13	16	22	22	34	8.5	10.1+-5.2	21.8+-10.4	16+-9.9
Bipolar Front to back	9	6	17	13	26	22	39	8.6	11.1+-5	23.9+-12.4	17.5+-11.1
Bipolar Front to back skip 1	7	6	15	13	22	19	34	13	10+-4.5	22.1+-8.9	16+-9.2
Bipolar Symmetrical	8	7	15	11	22	22	34	9.5	9.9+-3.6	22.1+-10	16+-9.5
Bipolar Left to Right	3	5	3.1	3.8	1.9	2.6	13	13	3.5+-0.9	7.6+-6.3	5.6+-4.7
Bipolar Right to Left	2	4	7.5	11	2.2	3.1	19	8	6.1+-4.1	8.2+-7.9	7.1+-5.9
CAR without Mastoid	7	8	19	13	30	16	30	9.9	11.9+-5.6	21.4+-10.1	16.6+-9.1

Table 3. Comparison based on Maximum average bitrate per minute obtained with BLDA, averaged over all subjects and sessions, for 8 channels electrode configuration

Subject	S1	S2	S3	S4	S6	S7	S8	S9	Average(S1-S4)	Average(S6-S9)	Average(all)
T7 & T8	8.8	11	25	19	26	22	49	19	15.9+-7.5	29.3+-13.7	22.6+-12.5
CAR	11	14	28	22	22	28	44	25	18.8+-7.8	29.7+-9.7	24.3+-10
Common Reference	13	12	19	19	16	25	34	17	15.9+-3.8	22.9+-8.4	19.4+-7.1
Laplacian 4	9.7	14	17	19	8.3	26	22	17	15+-4.2	18.4+-7.7	16.7+-6
Laplacian 8	11	14	19	22	13	26	39	17	16.7+-5.1	23.7+-11.3	20.2+-9
Bipolar Front to back	8.8	7.2	19	17	22	30	34	19	13.1+-6	26.4+-6.8	19.7+-9.3
Bipolar Front to back skip 1	8.8	9.7	19	19	26	22	39	15	14.2+-5.8	25.5+-9.9	19.8+-9.6
Bipolar Symmetrical	11	8.8	15	19	19	22	26	13	13.6+-4.6	20+-5.5	16.8+-5.8
Bipolar Left to Right	8.8	8.8	11	19	16	19	30	15	11.9+-4.9	20+-6.8	16+-7
Bipolar Right to Left	9.7	13	17	17	16	26	26	15	14.2+-3.6	20.7+-6.1	17.4+-5.8
CAR without Mastoid	11	15	28	17	22	28	39	17	17.8+-7.2	26.5+-9.3	22.1+-9

Table 4. Comparison based on Maximum average bitrate per minute obtained with BLDA, averaged over all subjects and sessions, for 16 channels electrode configuration

Subject	S1	S2	S3	S4	S6	S7	S8	S9	Average(S1-S4)	Average(S6-S9)	Average(all)
T7 & T8	7.7	11	25	22	26	39	56	22	16.4+-8.2	35.7+-15.2	26.1+-15.3
CAR	9.9	14	25	26	34	39	65	19	18.6+-7.9	39.2+-18.9	28.9+-17.3
Common Reference	11	11	19	22	30	34	44	16	15.8+-5.6	30.9+-11.6	23.4+-11.6
Laplacian 4	9.9	13	19	25	22	34	39	17	16.7+-6.6	28+-10.1	22.4+-9.9
Laplacian 8	9.9	11	22	22	26	34	39	15	16.4+-6.7	28.4+-10.4	22.4+-10.3
Bipolar Front to back	9.5	7.7	19	19	19	34	34	17	13.8+-6	26.1+-9.2	20+-9.8
Bipolar Front to back skip 1	9.2	9.7	19	22	26	30	34	19	15+-6.5	27.3+-6.3	21.2+-8.8
Bipolar Symmetrical	8.8	8	19	17	13	39	49	15	13.1+-5.5	29+-17.9	21.1+-14.9
Bipolar Left to Right	7.7	12	22	19	22	30	44	19	15.3+-6.5	28.8+-10.9	22.1+-11
Bipolar Right to Left	9.5	14	28	22	22	25	34	15	18.4+-8.3	24+-7.9	21.2+-8.1
CAR without Mastoid	9.9	13	28	19	30	39	65	17	17.5+-8	37.5+-20.1	27.5+-17.8

Table 5. Comparison based on Maximum average bitrate per minute obtained with BLDA, averaged over all subjects and sessions, for 32 channels electrode configuration

Subject	S1	S2	S3	S4	S6	S7	S8	S9	Average(S1-S4)	Average(S6-S9)	Average(all)
T7 & T8	13	11	22	30	34	39	65	17	19+-8.6	38.6+-19.7	28.8+-17.6
CAR	15	14	28	22	30	44	65	17	19.8+-6.6	38.8+-20.4	29.3+-17.3
Common Reference	11	9.9	25	19	30	34	56	13	16.3+-7	33.2+-17.7	24.8+-15.4
Laplacian 4	13	13	25	26	34	49	44	22	19.1+-7.2	37.3+-12.1	28.2+-13.4
Laplacian 8	13	11	28	28	34	34	49	15	20.1+-9.2	33.1+-14.1	26.6+-13.1
Bipolar Front to back	11	9.7	28	25	30	34	56	19	18.3+-9.4	34.8+-15.4	26.6+-14.7
Bipolar Front to back skip 1	11	8.8	28	25	30	39	49	16	18.2+-9.6	33.5+-14.1	25.8+-13.9
Bipolar Symmetrical	8.8	8.6	19	17	16	28	44	19	13.3+-5.3	26.7+-12.5	20+-11.4
Bipolar Left to Right	9.9	12	28	19	22	26	49	16	17.4+-8.1	28.4+-14.6	22.9+-12.4
Bipolar Right to Left	9.7	14	25	25	19	26	49	16	18.3+-7.6	27.6+-15.2	22.9+-12.2
CAR without Mastoid	15	14	28	22	30	39	56	19	19.8+-6.6	36+-15.5	27.9+-14