EEG Artifact Reduction in VEP Using 2-Stage PCA and N4 Analysis of Alcoholics

P. Sharmilakanna[1] and #Ramaswamy Palaniappan[2]
[1]*Faculty of Information Science and Technology, Multimedia University, Melaka, Malaysia*
[2]*Dept. of Computer Science, University of Essex, Colchester, United Kingdom (rpalan@essex.ac.uk)*

Abstract

In this paper, repeated applications of Principal Component Analysis (PCA) are proposed to reduce background electroencephalogram (EEG) artifact from multi-channel and multi-trial Visual Evoked Potential (VEP) signals. This will allow single trial analysis of VEP signals. PCA has been used for noise reduction but the method of repeated applications of PCA is novel. In the study here, PCA was applied in 2 stages. In the first stage, PCA was applied to multi-channel VEP signals from one trial. The output VEP signals from the first stage were used in the second stage, where PCA was applied to multi-trial VEP signals from a single channel. Simulation study using emulated VEP signals contaminated with EEG artifact shows significant improvement in signal to noise ratio using the method. It was then applied to study the electrophysiological differences between alcoholic and non-alcoholic subjects using N4 parameter. Hypothesis testing using t-test showed that alcoholics had significantly weaker and slower N4 responses as compared to non-alcoholics.

1. INTRODUCTION

Visual Evoked Potential (VEP) signals consists of oscillating potentials derived from the scalp surface using electrodes and are believed to originate from the neurons in the cortex (outer layer of the brain) [1]. They are a specific type of electroencephalogram (EEG) signal and are evoked during the perception of visual stimulus like seeing a picture. VEP signals have been applied in numerous neuropsychological studies and clinical purposes [1].

An artifact that corrupts VEP signals is background electroencephalogram (EEG). Averaging is commonly used to reduce the effects of EEG because VEP signals are loosely time-locked to the stimulus, thereby adding up with averaging while EEG will be reduced due to its random property [2].

This paper proposes the application of 2-stages of PCA to reduce EEG from VEP signals. PCA is a technique commonly employed to reduce the dimension of the feature set [3]. It also has been used to reduce noise from biomedical signals like EEG [4] and VEP [5]. Panerai *et al* [6] used PCA to discriminate between two classes for blood flow analysis, where the method also employed PCA to reduce noise from the blood flow measurements. Urbach *et al* [7] used the Karhunen Loeve Transform method (similar to PCA) to analyse VEPs obtained from normal, suspected multiple sclerosis and confirmed multiple sclerosis where the authors used only the first 5 principal components (PCs) to reconstruct the normal VEP signals and discarded the rest of the PCs as noise.

All these methods work on single stage PCA, i.e. PCA is applied only once. The method proposed here works by applying PCA twice; firstly with multi-channel VEP signals from one trial and secondly with multi-trial VEP signals from one channel. The novelty of the method lies in the 2-stage application. The method does not assume any property of VEP signals but require that VEP signals be recorded from many channels and across many trials (sessions). This requirement of multi-channel and multi-trial recordings is not a drawback for VEP signals because most VEP recordings are obtained from many channels and across many trials[1][8].

Although one-stage PCA might be sufficient to improve the SNR, second-stage PCA becomes important to further improve the SNR in cases involving VEP signals. This is as the EEG levels are comparable to the VEP signal levels [8].

The first-stage PCA reduces EEG from multi-channel VEP signals obtained from a single trial. VEP signals are more correlated from one channel to another as compared to EEG during visual perception. As such, PCA which uses eigen analysis of data covariance matrix can be applied to reduce EEG in VEP signals. The output VEP signals from the first-stage PCA are used by the second-stage PCA, which is applied to multi-trial VEP signals from a single channel.

The ability of the two-stage PCA to reduce EEG from VEP signals is shown through a simulation study using emulated VEP signals contaminated with EEG. Next, an experimental study using real VEP signals is conducted. The extracted single trial VEP signals after applying two-stage PCA are analysed in the low frequency domain using N4 parameter to investigate the electrophysiological differences between alcoholics and non-alcoholics. N4 responses which generally occur from 400-600 ms after stimulus onset, is used to measure the response to a newly recognised or incongruous information [9]. The t-test analysis is conducted using N4 amplitudes and N4 latencies to study the electrophysiological differences between alcoholics and non-alcoholics.

2. EMULATED VEP AND EEG SIMULATION

In this study, the VEP signals were emulated to match closely with the real VEP signals by creating VEP signals that have

[1] To remove background EEG through averaging requires many trials.

variability between channels and trials. Real VEP signals that are extracted during a stimulus perception are distinct between channels, but there exists similar components between the VEP signals from different channels for a subject. This situation was emulated in multi-channel VEP signals using combinations of Gaussian waveforms, each with different mean, variance and amplitude. Real VEP signals are loosely time-locked to the stimulus, so there are small variations between VEP signals from the same channel but different trials. This condition was emulated in multi-trial VEP signals with small variation in the amplitudes and latencies of the Gaussian waveforms.

Gaussian waveforms were chosen due to their suitability to emulate the real VEP signal components. This could be seen from Figure 1, which shows an example of a real VEP signal. It is possible to see that the real VEP could be constructed using multiple Gaussian type of waveforms with different means, variances and amplitudes. The EEG was constructed using whitening method of multi-channel EEG signals extracted while a subject was at rest. The results of applying the two-stage PCA to the emulated VEP contaminated with EEG will be shown illustratively and through SNR calculations.

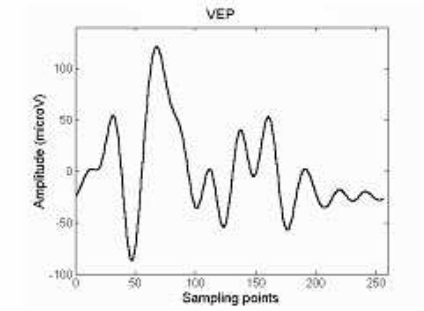


Fig. 1: Example of real VEP signal

VEP signal was emulated using a combination of five randomly selected waveforms from six Gaussian waveforms, each with different mean, variance and amplitude. Additional variations in the VEP signals were obtained using negative and/or positive amplitudes of Gaussian waveforms. The emulated VEP signals were later normalised to zero mean and unit variance.

The basic Gaussian waveform equation that was used is given below:

$$G(n) = \left[A / \sqrt{2\pi\sigma^2} \right] \exp\left(-(n-\mu)^2 / 2\sigma^2 \right), \quad (1)$$

where μ is the mean, σ is the standard deviation and A is the amplitude of the signal. The variation of μ, σ and A for the Gaussian waveforms were to emulate the variability between channels of real VEP signals. In this work, MATLAB[2] code below was used to generate the Gaussian waveform, *x*:

*x=A*exp(-((i-M).*(i-M))/(2*V))/sqrt(2*(22/7)*V),* (2)

where *A* is the amplitude, *V* is the variance, *M* is the mean and *i* is the sampling point. By varying the values of *A*, *V* and *M*, different Gaussian waveforms were obtained.

The real VEP signals differ from one channel to another (intra-trial variability) but as the example in Figure 1 shows; these VEP signals could be constructed from a few basic components. Inter-trial variability was created by varying latencies and amplitudes of the VEP signals from the same channels. This variability should be small to match the case of real VEP signals that have time-locking property and differ only slightly from one trial to another [1], [8]. Variability between trials was created by randomly varying the mean of the Gaussian waveform with a factor of ± 5 samples (to reflect latency differences), while the amplitude differences were created by randomly multiplying the amplitude of the Gaussian waveform with a factor of 0.8-1.2. An example of the emulated VEP signal is shown in Figure 2 (a).

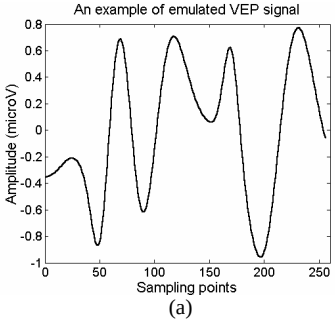
The EEG was constructed using whitening method, which is as follows. EEG signals were extracted while the subjects are at rest. These signals were first centered to remove the mean and then whitened to remove correlation between their components and to achieve unit variance. Assuming matrix $\mathbf{z}$ to represent the extracted signal, whitening seeks to obtain EEG matrix $\tilde{\mathbf{z}}$, where the covariance of matrix $\tilde{\mathbf{z}}$, *E* equals the identity matrix:

$$E(\tilde{\mathbf{z}}\tilde{\mathbf{z}}^{\mathbf{T}}) = \mathbf{I} \ . \quad (3)$$

A common whitening method is to use the eigenvalue decomposition of the covariance matrix $E(\mathbf{z}\mathbf{z}^{\mathbf{T}}) = \mathbf{E}\mathbf{D}\mathbf{E}^{\mathbf{T}}$, where $\mathbf{E}$ is the orthogonal matrix of eigenvectors of $E(\mathbf{z}\mathbf{z}^{\mathbf{T}})$ and $\mathbf{D}$ is the diagonal matrix of its eigenvalues, $\mathbf{D} = diag(d_1,....,d_n)$. Whitening was achieved using

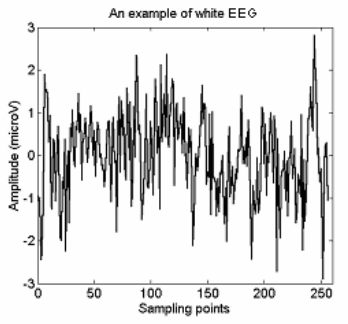
$$\tilde{\mathbf{z}} = \mathbf{E}\mathbf{D}^{-\mathbf{1/2}}\mathbf{E}^{\mathbf{T}}\mathbf{z} \ . \quad (4)$$

An example of whitened EEG signal is shown in Figure 2(b).



(a)

[2] Mathworks, Inc.



(b)

Fig. 2: Examples of (a) Emulated VEP signal (b) White EEG signal

The VEP signal with EEG artifact was constructed using

$$x(n)_{EEG+VEP} = x(n)_{VEP} + x(n)_{EEG} \ . \quad (5)$$

The signal to noise (SNR) of VEP signal to EEG was set approximately to 0 dB, i.e. the signal level was approximately equal to the EEG level. Emulated VEP signals contaminated with EEG for 50 channels across 20 trials were created.

3. EEG REDUCTION USING PCA

A. PCA

The VEP signals consist of two parts: signal and EEG. Therefore, using PCA, it is possible to separate EEG part from signal part (i.e. VEP) using the fact that the EEG subspace will constitute of principal components (PCs) with eigenvalues chosen below a certain threshold and eigenvalues with PCs above this threshold represent the signal subspace. Assuming matrix $\mathbf{x}$ to represent the extracted EEG corrupted VEP signal, the covariance of matrix $\mathbf{x}$ was computed using:

$$\mathbf{R} = E(\mathbf{x}\mathbf{x}^{\mathbf{T}}) \ . \quad (6)$$

Next, matrices $\mathbf{E}$ and $\mathbf{D}$, were computed where $\mathbf{E}$ is the orthogonal matrix of eigenvectors of $\mathbf{R}$ and $\mathbf{D}$ is the diagonal matrix of its eigenvalues, $\mathbf{D} = diag(d_1,....,d_n)$. The PCs were computed using

$$\mathbf{y} = \mathbf{E}^{\mathbf{T}}\mathbf{x}^{\mathbf{T}} \ . \quad (7)$$

In this work, percentage of total power (variance) retained was used to give the number of required PCs [3]. Using this method, PCs that account for 95% of the total power was assumed part of the signal in the first-stage PCA, while PCs that account for 99.8% of the total power was assumed part of the signal in the second-stage PCA. The PCs that account for the 5% and 0.2%, respectively account for EEG. These values were chosen after some preliminary simulations. The higher value of power retained in the second-stage PCA was to reflect the EEG, which decreases. The signal part of the VEP was reconstructed from the selected PCs using

$$\tilde{\mathbf{x}} = \hat{\mathbf{E}}\hat{\mathbf{y}} \ , \quad (8)$$

where $\hat{\mathbf{E}}$ and $\hat{\mathbf{y}}$ are the eigenvectors and PCs, respectively.

B. EEG reduction

Two-stages of PCA were applied to the emulated VEP signal contaminated with EEG given by (5). First, PCA was applied to the 50 channels of VEP signals from a single trial. The output VEP signals were applied again with PCA but using 20 trials of VEP signals from the same channel. This procedure is illustrated in Figure 3.

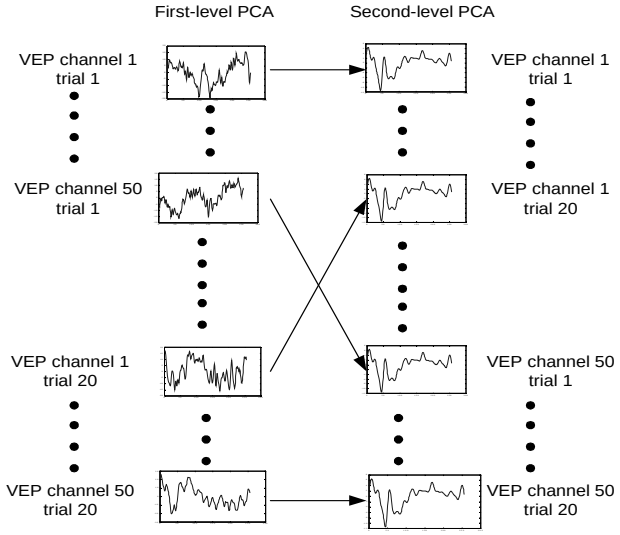


Fig. 3: First-stage and second-stage PCA

Using percentage of total power retained, the number of PCs to reconstruct the data was determined. This is more suitable for automated procedures as compared to other methods like scree graph test since it does not involve manual inspection. These PCs, which account for most of the variance in the data, can be assumed to represent the signal part of the VEP. The rest of the PCs can be considered to account for EEG in the data. Using this method, the first six PCs for first-stage PCA were selected, while for the second-stage PCA, only the first PC was selected. The numbers of PCs selected were in accordance with the creation of the emulated VEP signals. Because six basic Gaussian waveforms have been used to create the multi-channel VEP signals, six PCs were selected for the first stage PCA. This is an important result because it shows that the correct number of PCs was selected using the decided percentage of total power to retain.

With multi-channel real VEP signals, a few PCs might be sufficient to represent all the VEP signals and the correct number of PC selection is crucial to preserve only the signal part of the VEP signals and not EEG. The second-stage PCA used only the first PC because there was only one basic VEP signal present in the multi-trial VEP signals of the same channel. This situation is similar to multi-trial real VEP signals that are time-locked to the stimulus with small variations between the signals.

The first column of Figure 4 (at end of the paper) shows the emulated VEP signals contaminated with EEG, while the second column shows the VEP signals with EEG reduced by the first-stage PCA. The last column shows the VEP signals with EEG reduced further by the second-stage PCA. From the figure, it could be seen that the two-stage PCA has reduced EEG effects from the emulated VEP signals. Note also the improvements in SNR after first-stage PCA and second-stage PCA. Due to space constraints, only the graphical results from two VEP signals are shown. However, the reductions in EEG (i.e. improvements in SNR) were obtained for all the 50 VEP signals, which could be seen from the averaged SNR values.

4. EXTRACTION OF N4 PARAMETER FROM REAL VEP

This study used data from 20 subjects, where half of them were alcoholics and the rest half non-alcoholics. Measurements were taken from 64 electrodes placed on the subject's scalp, which were sampled at 256 Hz. The common electrode placement system is the 10-20 international method [10], which contains 19 active plus 2 reference electrodes. Here, the extension of the method was used to increase the number of electrodes to 64 as shown in Figure 5.

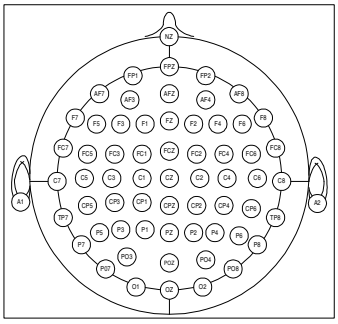


Fig. 5: 64 Channel Electrode System

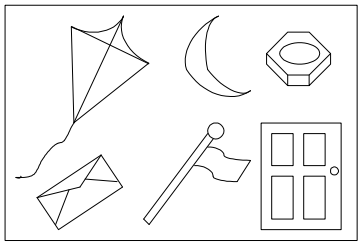


Fig. 6: Pictures from Snodgrass and Vanderwart set

The brain signals were recorded from subjects while being exposed to a single stimulus, which were pictures of objects chosen from Snodgrass and Vanderwart picture set [11] as shown in Figure 6. These pictures were common black and white line drawings like kite, door, bolt, flag, etc. executed according to a set of rules that provide consistency of pictorial representation. The pictures were normal pictures that were easily named. In other words, all the pictures were recognisable by the subjects. As all the pictures were all different (new information), this will evoke N4 potentials in the brain.

Eye blink contaminated brain signals were removed using a computer program written to detect signals in any one the frontal or prefrontal channels with magnitudes above 100 μV. These signals detected with eye blinks were then discarded from the experimental study and additional trials were conducted as replacements. The threshold value of 100 μV was used since blinking produces 100-200 μV potential lasting 250 milliseconds [1].

The subjects completed 40 trials of one-second measurements. Actually, the number of trials was slightly higher but after removing eye-blink contaminated artifacts, there were 40 trials. Figure 7 shows an example of the stimulus presentation. The interval between trials is 5.1s. The experimental set-up was designed by Zhang *et al* [12] for their studies on objects recognition using brain signals. Their study differed as they studied the P2 responses from alcoholics and non-alcoholics using averaged brain signals as opposed to single trial analysis of N4 responses in this study.

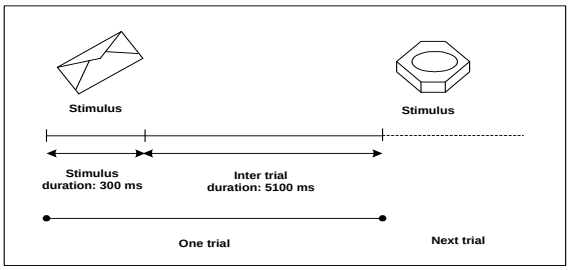


Fig. 7: Presentation of Snodgrass and Vanderwart picture stimulus

Next, the two-stage PCA was applied to reduce EEG and to obtain the VEP signals. These VEP signals were low pass filtered using a 9^{th} order Butterworth digital filter with a 3-dB cut-off frequency at 8 Hz. The cut-off frequency of 8 Hz was chosen based on the research by Almasy *et al* [9] because N4 responses are limited to this frequency range. Order 9 was used since it was sufficient to give a minimum attenuation of 30dB in the stop band with a transition band from 8 to 12 Hz. Forward and reverse filtering were performed to achieve zero phase response i.e. to avoid any phase distortion because Butterworth filter is a non-linear filter.

The standard t-test analysis was conducted to compare the means of N4 amplitudes and N4 latencies between alcoholics and non-alcoholics using significant value of 0.05. The t-test is a valuable common tool in statistical procedure and is normally used when comparing the means of two different groups.

Figure 8 shows the block diagram of the various stages involved in this study and Figure 9 shows the VEP responses from randomly selected alcoholic and non-alcoholic subjects.

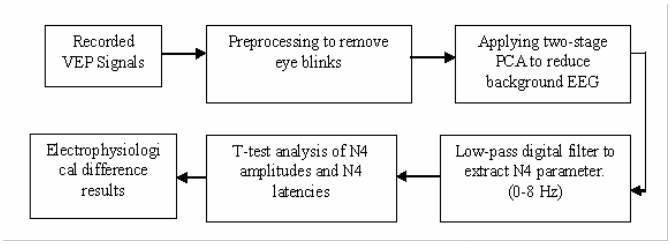


Fig. 8: The steps in single trial analysis of N4 parameter

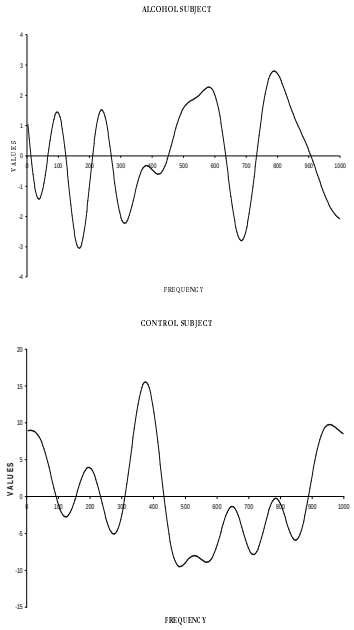


Fig. 9: N4 responses from alcoholic and non-alcoholic subjects

5. RESULTS OF T-TESTS

Due to space constraints the results of T-test for N4 amplitude and N4 latency are given only for 10 randomly selected channels as shown in Table 1. In the table, column 1 show results if there is any significant difference ($p<0.05$), while it is 0 if there is no significant difference ($p>0.05$). The results of N4 amplitude and N4 latency differences for all the active 61 channels are shown diagrammatically in Figures 10 and 11 for alcoholics and non-alcoholics, respectively.

TABLE 1: TWO-STAGE PCA RESULTS OF VEP SIGNALS

Channels	N4 Amplitude		N4 Latency	
	Results	Values	Results	Values
CP1	0	0.072110	0	0.317267
CP2	1	0.005808	0	0.800116
P3	0	0.114284	0	0.272554
P4	1	0.000206	0	0.606244
PZ	1	0.036459	0	0.396033
P8	1	0.001542	0	0.308845
P7	0	0.223731	0	0.668929
PO2	1	0.007119	0	0.196290
PO1	1	0.028246	1	0.017011
O2	1	0.002087	0	0.358329

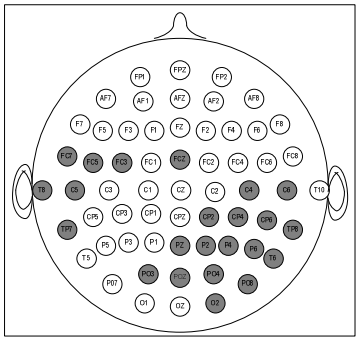


Fig. 10: T-test results of N4 amplitudes

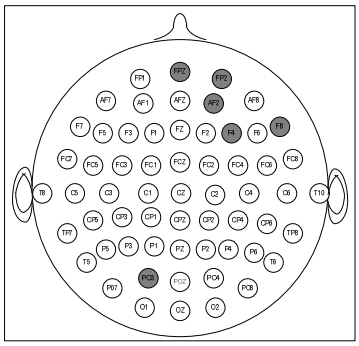


Fig. 11: T-test results of N4 latency for 61 channels

Figure 10 shows that there are many channels are shaded. The shaded channels indicate lower N4 amplitude values for alcoholics when compared to non-alcoholics. Figure 11 shows the results for t-test analysis of N4 latencies between alcoholics and non-alcoholics. The shaded channels show higher N4 latency for alcoholics as compared to non-alcoholics.

6. CONCLUSION

In this paper, two-stages of PCA have been proposed to extract single trials of VEP signals. In the simulation study, brain signals were emulated using VEP contaminated with EEG and the application of two-stage PCA improved the SNR of VEP signals, where the SNR improvements were obtained at both levels of PCA. The technique could be extended to more levels to further reduce noise, if necessary, where the odd-stage PCA works on multi-channel single trial brain signals, while the even-stage PCA work on multi-trial single channel VEP signal. The percentage of power retained (to select the PCs) must be gradually increased to reflect the decreasing EEG power. The reasonable number of levels would be two, though this should be determined by the application. Computational complexity will be the overhead of going to further levels.

Next, to conclude the results of t-tests analysis using single trial VEP signals; many of the channels exhibited significant lower N4 amplitudes for alcoholics as compared to non-alcoholics. This indicated that alcoholics may have difficulty in recognition and/or memory. Some of the

channels exhibit significant higher N4 latencies for alcoholics as compared to non-alcoholics, which indicate the possibility of slower recognition for alcoholics. Therefore, the results show some form of persistent electrophysiological impairments caused by long term alcohol use. This is true although the alcoholics abstained from drinking for a month before participating in the study. However, further study would be required to determine the actual impairments shown by the N4 amplitude and latency differences.

ACKNOWLEDGEMENT

We would like to thank Prof. Henri Begleiter at the Neurodynamics Laboratory at the State University of New York Health Centre at Brooklyn, USA who generated the raw VEP data.

REFERENCES

[1] Misulis, K.E., Spehlmann's Evoked Potential Primer: Visual, Auditory and Somatosensory Evoked Potentials in Clinical Diagnosis, Butterworth-Heinemann, 1994.

[2] Aunon, J.I., McGillem, C.D. and Childers, D.G., "Signal Processing in Event Potential Research: Averaging and Modelling," CRC Crit. Rev. Bioeng., vol. 5, pp. 323-367, 1981.

[3] Jolliffe, I.T., Principal Component Analysis, Springer-Verlag, 1986.

[4] Sadasivan, P.K., and Dutt, D.N., "SVD based technique for EEG reduction in electroencephalographic signals," Signal Processing, pp. 179-189, vol. 55, 1996.

[5] Lange, D.H., and Inbar, G.F., "Variable Single-Trial Evoked Potential Estimation via Principal Component Identification," Proceedings of IEEE EMBS International Conference, pp. 954-955, 1996.

[6] Panerai, R.B., Ferreira, A.L.A.S., and Brum, O.F., "Principal component analysis of multiple non-invasive blood flow derived signals," IEEE Transactions on Biomedical Engineering, pp. 533-537, vol. 35, no. 7, 1988.

[7] Urbach, D., Gur, M., Pratt, H., and Pelad, R., Time domain analysis of VEPs," Invest. Opthamol. Visual Sci., pp. 1379-1394, vol. 27, 1986.

[8] Kriss, A., "Recording Technique," in Halliday, A.M. (ed), Evoked Potentials in Clinical Testing, Churchill Livingstone, 1993.

[9] Almasy L et al, "Genetics of Event-Related Brain Potentials in response to a Semantic Priming Paradigm in Families with a History of Alcoholism," American Journal of Human Genetics, vol. 68, pp. 128-135, 2001.

[10] Jasper, H., "The ten twenty electrode system of the international federation," Electroencephalographic and Clinical Neurophysiology, no. 10, pp. 371-375, 1958.

[11] Snodgrass, J.G., and Vanderwart, M., "A Standardized Set of 260 Pictures: Norms for Name Agreement, Image Agreement, Familiarity, and Visual Complexity", Journal of Experimental Psychology: Human Learning and Memory, vol. 6, no.2, pp. 174-215, 1980.

[12] Zhang, X.L., Begleiter, H., Porjesz, B., Wang, W. and Litke, A., "Event related potentials during object recognition tasks," Brain Research Bulletin, vol. 38, no. 6, pp. 531-538, 1995.

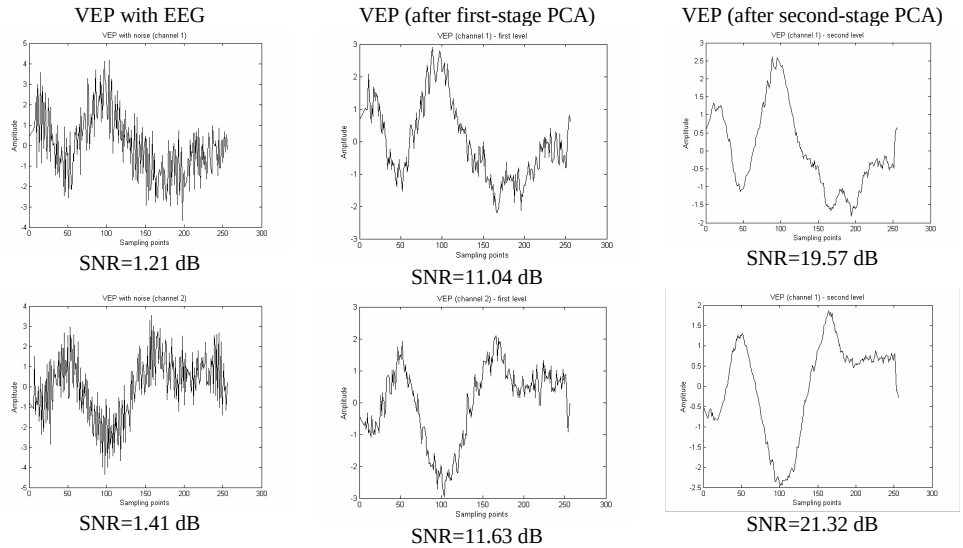


Fig. 4: VEP signals (a) with EEG (b) after first-stage PCA (c) after second-stage PCA. Note the SNR improvement using first-stage and second-stage PCA (Also shown are the average SNR values from 50 VEP signals)