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Augmenting a SSVEP BCI through single cycle analysis and phase weighting

John J Wilson and Ramaswamy Palaniappan
BCI Group, School of Computer Science and Electronic Engineering
University of Essex, Wivenhoe Park, Colchester, UK
Email: jjwils@essex.ac.uk, rpalan@essex.ac.uk

***Abstract*—Single cycle analysis of the Steady State Visual Evoked Potential (SSVEP) response allows use of standard significance tests to determine a subject's gaze. This allows standard criterion levels to be set across all subjects rather than individually by empirical analysis. Furthermore once a subject's gaze has been classified it is possible to extract a notion of expected phase to a SSVEP stimulus. This expected phase value can then be used to augment classification of attention to a four class Brain Computer Interface system improving transfer rates.**

***Index Terms*—Brain Computer Interface (BCI), Steady State Visual Evoked Potential (SSVEP), Electroencephalogram (EEG)**

I. Introduction

SSVEP is an excellent candidate as a paradigm for a BCI due to the robust nature of the EEG response to flashing stimuli in most subjects. It has been well documented in previous studies [1, 2] that the attention of a subject to a particular stimulus can be detected by examining the frequency spectra of the recorded EEG for peaks in amplitude at the corresponding flashing rate. Less well studied is the contribution of the individual response from each stimulus flash (single cycle) to the summation of the steady state response over time [3]. Peaks in amplitude measured over intervals encompassing more than one cycle can occur through a collection of large responses with low phase coherence or through smaller responses that are phase locked.

Typically SSVEP BCI's utilise a computer monitor [4] or LED'S [5] to present flashing stimuli to a subject. Each stimuli flashes at a unique rate and is tagged to an action or trigger eg, the selection of numbers on a keypad. The user simply attends to the stimulus that corresponds to the action that they would like to perform. Spectral analysis of the recorded EEG should provide evidence of the stimulus attended by the user. The most commonly used tool for spectral analysis is the Fast Fourier Transform (FFT). The result of the FFT operation are 'bins' containing complex numbers made up of two orthogonal (real and imaginary) values. These values are ubiquitous to Cartesian co-ordinates x and y and can be easily translated into more recognisable phase and amplitude values.

The SSVEP response is a phase locked response i.e. successive cycles measured at identical start and end points should have identical phase. Bins corresponding to frequencies where no SSVEP response should be evident such as those of non and unattended stimuli, should contain regular EEG i.e. non response regarded as noise. Noise is not phased locked so summed vectors should in effect cancel each other out producing no enlarged amplitude over multiple cycles. Therefore attention detection criteria encompassing bins which show increased magnitude in amplitude should be satisfactory. However increased summed vector amplitudes can also occur from individual cycles that are out of phase with enlarged amplitudes. Such responses do not fit the description of an SSVEP response in that increased amplitude should occur from additive in phase cycles. It therefore seems valuable to inspect the SSVEP response on a single cycle level. It is possible to compare the effect of the individual amplitudes and the phase coherence of the single cycles making up a summed vector by monitoring if changes in summed amplitude and phase coherence are linked.

II. Methods

A. Experimental Setup

In this study a LCD monitor was used to display four unique flashing stimuli. The stimuli were constructed using the Psychophysics toolbox in Matlab. The refresh rate of the monitor was 60Hz. It is only possible to flash stimuli at a rate that is an integer multiple of the display base rate (1/60) = 0.0167s. To this end the rates 8.574Hz, 12Hz, 15Hz and 20Hz were chosen as flashing rates of the stimuli.

Five healthy subjects participated in the study, aged 18 – 54yrs. Four subjects had normal vision, one subject had corrected to normal vision. All subjects were naive to the BCI equipment and paradigm. Subjects were seated in a position of comfort to their choosing with the centre of the LCD monitor level with their eye line at a distance of 1.25m. Subjects were asked to gaze at a predefined flashing stimulus from the set for a duration of 4 seconds defining 1 trial. Five trials were performed consecutively with a rest period of 10s between each trial where subjects were free to relax their gaze. This process was repeated for each of the four flashing stimuli providing 20 trials in total per subject. The order in which the subjects viewed the flashing boxes was consistent between subjects.

EEG was collected using the BioSemi ActiveTwo system from scalp location Oz at a rate of 512Hz. The recorded data was subsequently analysed offline in Matlab. Data was resampled at 300Hz and bandpass filtered between 5 – 45Hz. Filtering is used to remove AC power interference (50Hz UK system) and low frequency rhythms. As mentioned previously re-sampling is required to ensure that epochs encompass complete cycles exactly. EEG data of lengths 35, 25, 20 & 15 points corresponding to single cycles of the 8.574Hz, 12Hz, 15Hz and 20Hz stimuli respectively, were extracted for the entire duration of each trial. A Fast Fourier Transform was used to extract the orthogonal components (F_m) for each single cycle.

B. *Information Transfer Rate (ITR)*

Bit Rate is a standard measure of communication systems and can be used to evaluate BCI performance. It depends on the number of available targets (*N*) and the probability of selecting a target (*P*) and is calculated by equation (1).

$$Bit\ rate = \ log_2 N + Plog_2 P + (1-P)log_2 \frac{1-P}{N-1} \quad (1)$$

The ITR measured in bits/min is calculated by the product of the bit rate and the number of targets that can be selected in 60 seconds.

C. *Subject Attention Detection Methods*

1) *Phase Locking and Summed Amplitude*

To obtain the amplitude and phase of single cycle responses individually we must present an EEG data length that encompasses exactly 1 cycle. This enforces a constraint that the flashing rates of the stimuli must be integer divisors of the sampling rate.

Phase coherence over cycles can be measured by way of the Phase Locking Index (PLI) calculation shown in equation (2). The PLI is a value ranging from 0 – 1 with 1 indicating a completely phase coherent response (all cycles have exact phase) and 0 indicating a completely incoherent response with cycles having phase equally spread about 360 deg. Summed amplitude is simply the sum of the amplitudes of each cycle that have passed and calculated by equation (3).

$$PLI_m = \left| \frac{1}{N} \sum_{n=1}^{N} \frac{F_m(n)}{|F_m(n)|} \right| \quad (2)$$

$$AMP_m = \left| \sum_{n=1}^{N} F_m(n) \right| \quad (3)$$

Each calculation is computed after one cycle and then recalculated as each new cycle passes. If summed amplitude is constructed entirely by phase coherence then changes in the two measures should be linked over paired cycles.

2) *Single Cycle Analysis of Amplitude and Phase – Hotelling's t^2 test*

As discussed previously the output of the FFT operation at each bin are a pair of orthogonal values which correspond to the x and y Cartesian co-ordinates defining the vector representing amplitude and phase. We can submit these values to a multivariate significance test known as Hotelling's t^2 test. The mean expected vector (that of unattended stimuli) should be zero as the phase of noise vectors is random and thus x and y points should cancel each other out. The t^2 test provides us with a probability that a mean vector diverging from zero (which we define as a SSVEP response vector) is due to chance (*P* value). This *P* value can then be used as detection criteria to classify the attended stimuli.

3) *Phase Weighted t test*

In the previous section we determined a response was present when the mean vector deviated from zero enough to reach significance at the $P<0.01$ level. We can record the average phase of the cycles that occurred when the response was deemed significant to create a notion of expected phase to each stimulus for every subject. Then for all future trials a simple weighting system based on actual phase (θ) and expected phase (θ_{exp}) can be applied to the amplitudes of each cycle as defined in equation 4.

$$weight = \cos(\theta - \theta_{exp}) \quad (4)$$

The weighting system produces a weight of 1 if phase and expected phase are equal and -1 if phase and expected phase are 180 apart. The determined weight is then multiplied by the amplitudes of each single cycle response. This is akin to projecting the two dimensional plane orthogonal values onto a one dimensional plane of expected phase. This transforms our multivariate two tailed t^2 test into a more common uni-variate one tailed *t* test [6]. It is crucial that the test is one sided and to the right as we want to test for means above zero and not below due to the effect of the weighting system. If the test was two sided then responses 180 deg out of phase (polar opposite) would become false positives. Significance was again defined as the $P < 0.01$ level. Where multiple trials of a stimulus reached significance in the t^2 test, the trial in which the most cycles had elapsed before significance was reached was used for the calculation of expected phase in the weight equation (6). The phase weighted method was then used to classify the remaining trials in its own group and that of the other targets. A settling period of half the frequency of the stimulus being tested was applied. This meant that the minimum time a decision could be made was 0.5s.

III. RESULTS

A. Detection Methods

1) Amplitude Vs PLI

Table I shows the classification accuracy on the recorded dataset when using Summed Amplitude and PLI values as detection methods for attention. Recorded EEG from 1 second after stimuli onset was compared for each subject over each of the 20 trials. For the case of the Summed Amplitude detection method the bin corresponding to each presented stimuli were compared, with the one holding maximum summed amplitude classified as the attended stimulus. The same method was applied for phase coherence but using the PLI result.

The accuracy that would occur by chance would be 25%. Accuracy was just better for the Summed Amplitude detection method at 55% compared to the phase coherence method at 51%. The PLI calculation removes all amplitude information, reducing each single cycle to unit value. This may lead to degraded performance because SSVEP is an amplitude modulated response, that is greater attention to the stimuli should bring about a larger single cycle amplitude. When we remove this information, we gain in that noise amplitudes are reduced, but lose in that signal amplitudes are also lost. The net effect is a reduction in classification accuracy. However the difference between methods is not statistically significant.

a) Summed Amplitude and PLI Detection Methods classify unique trials independently

It is interesting to note that in some trials Summed Amplitude and PLI methods successfully classified subjects' attention uniquely. Also Summed Amplitude and PLI did not track each other entirely over cycles. E.g. an increase in Summed Amplitude did not always coincide with an increase in PLI. This would signify that valuable information from the SSVEP response is carried in the amplitudes of individual response cycles and the phase coherence of collective cycles. Thus a detection method that incorporates both features may perform better.

2) Single Cycle Analysis of Amplitude and Phase –t^2 test

Table I shows the performance of the t^2 test at 1 second after stimuli onset. This method yields a poorer bit rate over the dataset compared to the previous Summed Amplitude and PLI methods in this experiment. Again the difference between methods is not statistically significant.

a) Improving Bit Rates – Accuracy Vs Speed

Table II shows the performance of the t^2 test method where a decision is only made when significance at the 1% level ($P<0.01$) was reached for a stimulus. There is an improvement in accuracy (false positives reduced), but as expected more time is taken to make a decision. However, the net effect on bit rate is positive, due to the structure of the bit rate equation (4). The resulting ITR is doubled to 28.09 bits/min compared to 13.96 bits/min of the previous method while only increasing average time to make a decision from 1.00 to 1.56 seconds.

3) Phase Weighted t test

Table II also shows the classification rates for the phase weighted *t* test method. Accuracy is improved from 53% to 67% compared to the t^2 method although average time to detect rose from 1.56s to 1.68s. This is due to trials that were detected incorrectly in the t^2 method being correctly detected by the phase weighting approach but taking a longer time classify. All trials correctly classified by the previous method are also correctly classified by this method in the same time or shorter. The effect is an almost doubling of the ITR from 28.09 bits/min without phase weighting to 44.09 bits/min with phase weighting. The improvement in ITR between the methods is statistically significant at the 5% level ($P= 0.0104$).

TABLE I
CLASSIFICATION PERFORMANCE OF SUMMED AMPLITUDE, PLI & t^2 TEST ATTENTION DETECTION METHODS
1S FROM STIMULUS ONSET

Detection Method	Subject	Accuracy (max/min/average)	ITR (bits/min)
Summed Amplitude	1	1.00/0.40/0.60	23.70
	2	0.80/0.40/0.60	23.70
	3	0.80/0.20/0.50	12.45
	4	0.80/0.40/0.55	17.64
	5	1.00/0.00/0.50	12.45
		100%/20%55%	**19.37**
PLI	1	1.00/0.40/0.70	38.59
	2	0.80/0.20/0.50	12.45
	3	1.00/0.00/0.50	12.45
	4	0.80/0.00/0.45	8.13
	5	1.00/0.00/0.40	4.68
		100%/0.00%51%	**15.26**
t^2 Test	1	1.00/0.20/0.50	12.45
	2	0.80/0.40/0.55	17.64
	3	1.00/0.20/0.55	17.64
	4	0.80/0.20/0.45	8.13
	5	1.00/0.20/0.55	17.64
		100%/20%/52%	**13.96**

TABLE II
CLASSIFICATION PERFORMANCE OF t^2 TEST & PHASE WEIGHTED *t* TEST ATTENTION DETECTION METHODS

Detection Method	Subject	Accuracy (max/min/average)	Time (min/max/average)(s)	ITR (max/min/average)(bits/min)
t^2 Test	1	1.00/0.00/0.60	1.05/2.17/1.29	114.29/0.00/40.57
	2	0.80/0.00/0.35	0.73/2.10/1.12	35.30/0.00/9.59
	3	1.00/0.20/0.65	1.00/2.25/1.62	119.60/0.27/50.87
	4	1.00/0.40/0.55	0.95/3.47/1.93	80.36/1.35/22.31
	5	0.80/0.20/0.50	1.00/3.15/1.84	45.98/0.19/19.00
		100%/0.00%/53%	**0.73/3.47/1.56**	**119.60/0.00/28.09**
Phase Weighted *t* test	1	1.00/0.40/0.75	0.82/1.87/1.37	129.73/12.74/58.94
	2	1.00/0.20/0.55	0.73/3.38/2.01	64.29/0.83/20.91
	3	1.00/0.20/0.70	0.96/2.25/1.68	125.44/0.27/58.07
	4	1.00/0.40/0.70	0.83/2.68/1.70	80.36/2.61/33.36
	5	1.00/0.20/0.65	0.93/2.95/1.68	128.57/0.61/49.21
		100%/20%/67%	**0.73/3.38/1.68**	**129.73/0.27/44.09**

IV. DISCUSSION

The results show that Summed Amplitude and PLI are not always related on a cycle by cycle basis. This indicates that summed amplitude does not fully represent phase coherence of single cycles. When used as classification features summed amplitude and phase coherence offer similar performance but classified some responses uniquely. This suggests that there is important information related to SSVEP response in amplitude and phase coherence.

A t^2 test was then used to classify attention with the motivation of combining both measures. The results were shown not to be significantly different from previous two methods. However for the t^2 method no stimuli were completely incorrectly classified as occurred for the Summed Amplitude and PLI Methods.

The application of thresholds allows epochs to continue being supplied until the t^2 method reaches significance, rather than making a decision after at set time point. This increases the ITR by improving accuracy rates at the sake of an increase in time taken to classify a response. This will always be the case due to the nature of the bit rate equation (1). If we were to apply thresholds to the Summed Amplitude and PLI methods then thresholds would have to be set for each subject independently through empirical analysis of their SSVEP response. However use of a statistical test such as t^2 allows a common threshold to be set across all subjects based on standard significance levels without individual inspection.

The t^2 test was then used to gather a notion of expected phase to each SSVEP stimulus for every subject. The expected phase response to a stimulus frequency appears to be subject specific and could define the latency between detecting and processing the stimuli. This expected phase was then used to construct a weighting system which projected the FFT results at each bin of interest onto an expected phase plane. Performance with this phase weighted system improved significantly over the previous classification methods. Accuracy rates improved due to reduction of false positives. This is likely due to noise vectors which may have previously corrupted the Summed Amplitude, PLI and t^2 test methods. In the phase weighted classifier these noise vectors are assigned low or negative weighting so their effect was greatly reduced. In addition with the phase weighted method there were no individual trials where false positives occurred where they had not occurred with the previous detection methods.

The ITR achieved by the final method of phase weighting compares favourably with previous studies. It has been suggested that further improvements in SSVEP BCI can be achieved by careful selection of channel location, stimulus frequencies and speed of selection (data lengths) on a per subject basis [7]. This study, using the final method of phase weighting achieved an average ITR of 44.09 bits/min over 5 subjects with a lowest subject bit rate of 20.91 bits/min. Importantly, channel location, stimulus frequencies and thresholds are fixed over all subjects. Although better rates may be achieved through adjusting individual subject's parameters by empirical analysis, this is at the expense of designing a future online system with low training phase and low cost that is able to be used quickly by all subjects.

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