Changes in EEG and HRV during Event-Related Attention

Sun K. Yoo, Chung K. Lee

Abstract**—**Determination of attentional status is important because working performance and an unexpected accident is highly related with the attention. The autonomic nervous and the central nervous systems can reflect the changes in person's attentional status. Reduced number of suitable pysiological parameters among autonomic and central nervous systems related signal parameters will be critical in optimum design of attentional devices. In this paper, we analyze the EEG (Electroencephalography) and HRV (Heart Rate Variability) signals to demonstrate the effective relation with brain signal and cardiovascular signal during event-related attention, which will be later used in selecting the minimum set of attentional parameters. Time and frequency domain parameters from HRV signal and frequency domain parameters from EEG signal are used as input to the optimum feature parameters selector.

Keywords**—**EEG, HRV, attentional status.

I. Introduction

Heart rate variability (HRV) and the spontaneous electrical activity of an electroencephalogram (EEG) signal vary with event-related, short-term attention. Previous studies have described the inter-relationship between attention and physiological responses using HRV and EEG signals [1]. However, these results mainly analyzed the correlation between the qualitative changes in the HRV and the EEG as a single parameter during event-related external stimuli. Therefore, the correlation coefficient was low, as they were only comparing a few variables. There have been few trials that have quantitatively examined the direct correlation of the electrical potentials of the brain and the dynamic activity of the cardiovascular system using EEG signals and HRV features.

The spontaneous activity of the EEG signal reflects specific frequency band changes. During event-related, short-term attention, the midline changes in theta (4-7.5Hz) and alpha (7.5-12Hz) signal activities have been used to analyze the mental state [1]. Theta rhythm increases when the subject is asked to attend to external stimuli or to perform mental tasks or meditation. Conversely, the alpha rhythm reflects physiological responses more so than the cognitive process, so alpha decreases during event-related stimuli [2]. Klimesch reported that the theta/alpha ratio is a critical indicator that should increase during event-related stimuli [2]. A state of psychological arousal such as that seen in response to event-related stimuli induces not only electrical changes in the EEG signal but also changes in the cardiovascular system [3].

Event-related stimuli have been found to affect the HRV parameters (beat interval, SDNN, RMSSD, NN50, LF/HF, peak amplitude, and spectral power) derived from PPG measurements, and these changes represent the reactions of the sympathetic and parasympathetic nervous systems with the changing mental state. While the sympathetic system significantly activates during attention and tension states, the parasympathetic system shows strong activation in resting and calm conditions.

This study aims to enhance the correlation coefficient, R^2, between HRV features and the theta/alpha ratio by evaluating multiple features using linear regression and comparing the values obtained to that of a single feature. In this way, we can postulate the degree of inter-relationship between the quantitative changes in HRV features to the theta/alpha ratio by increasing the dimensional space.

II. Material and Method

A. Experimental Design

The biological signals were recorded on two-channel amplifiers (Biopac MP150 TM) with one-channel with electroencephalography capabilities (EEG; central Cz using a GRASS electrode with conductive gel) and one with photoplethysmography (PPG; index finger using a transmissive sensor). The signals were then digitized at a sampling rate of 1000 Hz. The EEG electrodes were positioned at Cz in the midline, right earlobe (reference), and forehead (ground). The high pass filter of the EEG signal was set to 0.5 Hz, and the low pass filter was 100 Hz. The 60 Hz notch filter was on at all times. The high pass filter of the PPG signal was set to 0.5 Hz and the low pass filter was 10 Hz. The event-related attention was performed as follows: The numbers from 1 to 9 were recited randomly through the headset for 9 minutes, and the subjects pressed the spacebar on the keyboard when the designated number was spoken.

B. Feature Extraction and Linear Regression

The segmentation lengths of both EEG and PPG were fixed at 3 minutes. The status of attention was measured for 9 minutes, and it consisted of three independent segments of 3 minutes for value extraction. Through manual inspection, the external noise (motion, cough, etc.) judged as irrelevant to attention was eliminated. For the EEG frequency analysis, Fourier transformation was used. The ratio of the spectral power of the theta (4~7.5Hz) wave to that of the alpha (7.5~12Hz) wave was used as the measure of attention [4].

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The signal from the PPG sensor illustrates not only the tempo of the heart but also the blood pressure by heart contraction, so the HRV value was extracted to analyze the variation from peak to peak, and it was used to monitor the relative changes in blood pressure using the difference in peak pulse amplitudes. As HRV parameters, the LF/HF (Low Frequency/High Frequency) in the frequency domain, the beat interval in the time domain, SDNN (Standard Deviation of Normal to Normal R-R interval, where R is the peak of a QRS complex), RMSSD (Root Mean Square of Successive Heartbeat Interval Differences), NN50 (successive Normal to Normal intervals differing more than 50 msec), the average value of the peak amplitude, and the value of the spectral power in the frequency domain were extracted as the indicative values of the activity of the cardiovascular system [5].

The number of rows in the datasets was 22 (for 22 subjects) and the number of columns was equal to the number of the features (which was seven). The feature selected to be extracted from PPG was used as the observation data X_i , and the theta/alpha value extracted from the EEG in the dataset was used as the reference label Y_i . Equation (1) is the equation of multiple linear regression. In order to calculate the β value, the general linear modeling method based on the least mean square was used [6].

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \qquad (1)$$

III. Result

The results shown in Fig. 1, { R^2_{case1}, R^2_{case2}, ... , R^2_{case7} }, revealed significant correlations between multiple combined features in the cardiovascular system and the theta/alpha ratio in the spontaneous EEG rhythm. Observation of the average values of R^2 indicated that high dimensions of combined features had higher R^2 than did the low dimensions. To determine the R^2 values in high dimensional space compared to those of the two-dimensional spaces, we identified the main effects of the seven chosen features {beat interval (*1*), SDNN (*2*), RMSSD (*3*), NN50 (*4*), LF/HF (*5*), peak amplitude (*6*), spectral power (*7*)}.

Table I outlines the results of the linear regression of all combinations using six out of seven features (${}_7C_6$=7). Tables I-III demonstrate which parameters have more significant effects on the R^2 value. In addition, when the features were at the center, the R^2 values at the intersection of the horizontal axis and the vertical axis were recorded. Among all of the combinations of intersections, the location of each R^2 value was independent from those of the others; cases of overlap were marked with a dash.

The average of the R^2 values of all cases of combinations with six components was 0.58.

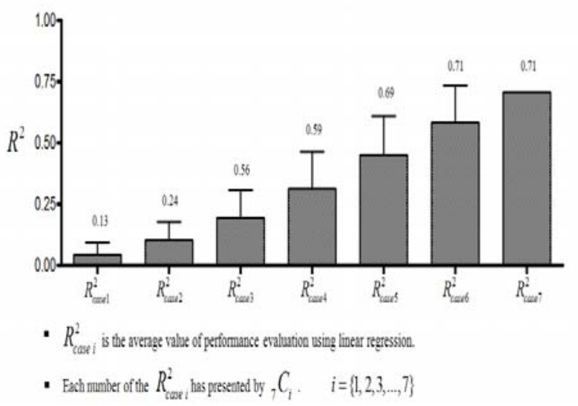

Fig. 1 The results of linear regression for the combined features (R^2 average, standard deviation, and maximum value)

TABLE I
R^2 Values of Linear Regression for Six-Dimensional Spaces

	2	2	2	2	2	3
	3	3	3	3	4	4
	4	4	4	5	5	5
	5	5	6	6	6	6
	6	7	7	7	7	7
1	0.581	0.601	0.670	0.696	0.563	0.269
2	-	-	-	-	-	0.706

* R^2 values over 0.58 were highlighted at the intersection of the horizontal axis and the vertical axis.

Table II shows the R^2 value that resulted from all possible combinations of four components (${}_7C_4$=35). The average R^2 value was 0.31, less than the average of the combinations with higher dimensions [avg (${}_7C_6$) =0.58, avg (${}_7C_5$) =0.45]. The common features of the highlighted R^2 values are the intersection with SNDD(*2*) and the relatively high R^2 value of the combinations that included SDNN(*2*) and RMSSD(*3*), {R^2=0.590; *2,3,5,7*}. Among the combinations of four components, the R^2 values of all the combinations based on {*2,3,5*} were the highest, and they are as follows: {R^2=0.558; *1,2,3,5*}, {R^2=0.56; *2,3,4,5*}, {R^2=0.583; *2,3,5,6*}, {R^2=0.590; *2,3,5,7*}

TABLE II
R^2 Values of Linear Regression for Four-Dimensional Spaces

	2	2	2	2	2	2	2	2	2	2
	3	3	3	3	4	4	4	5	5	6
	4	5	6	7	5	6	7	6	7	7
1	0.475	0.558	0.273	0.270	0.397	0.151	0.212	0.343	0.389	0.408

	3	3	3	3	3	3	4	4	4	5
	4	4	4	5	5	6	5	5	6	6
	5	6	7	6	7	7	6	7	7	7
1	0.262	0.265	0.266	0.138	0.130	0.022	0.176	0.187	0.175	0.139
2	0.563	0.456	0.495	0.583	0.590	0.510	0.326	0.345	0.359	0.406
3	-	-	-	-	-	-	0.249	0.254	0.253	0.138
4	-	-	-	-	-	-	-	-	-	0.174

* R^2 values over 0.31 were highlighted at the intersection of the horizontal axis and the vertical axis.

Table III displays the number of times a particular feature was excluded from combinations that correspond with the R^2 cells highlighted in Tables I, II. The cells included were those with larger R^2 than the average ($_7C_6$=0.58, $_7C_5$=0.45, $_7C_4$=0.31, $_7C_3$=0.19).

The sum of these values for each feature gives an idea of which feature {1, 2, 3, 4, 5, 6, 7} of the cardiovascular system has the most significant correlation with EEG changes. To determine this, we considered that the values that were excluded more often (those with a higher sum) had a lower significance. Therefore, for all of the features, the smaller is the sum, the more important the factor is for determining the R^2 value.

TABLE III
NUMBER OF EXCLUDED FEATURES FOR LARGER THAN AVERAGE R^2

	Counted values for excluded feature							
	1	2	3	4	5	6	7	
R^2 of 6 dimensional space	1	0	0	1	1	1	1	$R^2 \geq 0.58$
R^2 of 5 dimensional space	4	0	1	5	4	4	4	$R^2 \geq 0.45$
R^2 of 4 dimensional space	10	0	8	8	6	8	8	$R^2 \geq 0.31$
R^2 of 3 dimensional space	11	4	5	8	8	10	10	$R^2 \geq 0.19$
SUM	26	4	14	22	19	23	23	-

IV. DISCUSSION AND CONCLUSION

Alpha and theta rhythms of EEGs respond in different and opposite ways. Studies have found that, with increasing task demands, theta synchronizes, whereas alpha desynchronizes [1]. Theta changes associated with an external stimulus have been attributed to hippocampal function, as activation of this brain region is correlated with increased theta rhythms on EEG [5]. With respect to the components theta/alpha, our experimental results are in agreement with those of Klimesch, who reported that the theta power increases and the alpha power decreases during phasic event-related changes [2]. The inter-relationship of the theta/alpha ratio and the components of the cardiovascular response are highly significant in the combinations with more than three dimensions that included SDNN (*2*), RMSSD (*3*) and LF/HF (*5*). The time domain measurements SDNN (*2*) and RMSSD (*3*) are related to activation of the ANS, and these have greater physiologic significances than do beat interval (*1*), NN50 (*4*), LF/HF (*5*), peak amplitude (*6*), or spectral power (*7*).

The SDNN mostly reflects the fluctuation of heart rate behavior in the cardiovascular system. However, it cannot detect subtle changes in heart rate dynamics because the changes in heart rate occurring over seconds to minutes are obscured by slower changes [7]. In order to have a statistically significant correlation with theta/alpha, it must be combined with the other parameters of HR variability such as the RMSSD (3), NN50 (*4*), LF/HF (5), peak amplitude (*6*), and spectral power (*7*). Therefore, the analysis of HRV features can be used as a non-invasive assessment of cardiovascular autonomic regulation of the heart during the brain's potential activity [3].

Meanwhile, the pulse amplitude (peak amp) in the PPG signal that illustrates the changes in blood pressure with a faster heart rate caused by mental arousal and the spectral power (band limited: 0.04-0.4Hz) also affect the R^2 value. However, the effect is relatively small compared to those of SDNN (*2*), RMSSD (*3*), and LF/HF (*5*) [5]. The larger is the degree of the input vector applied to the regression, the more significant is the R^2 value of the cardiovascular system and the activity of EEG; in Table III, the order of influence on the correlation coefficient is as follows: SDNN >> RMSSD> LF/HF> NN50> peak amp= spectral power> beat-interval.

In conclusion, the features of the cardiovascular response to stimuli {beat-interval(*1*), SDNN(*2*), RMSSD(*3*), NN50(*4*), LF/HF(*5*), peak amp(*6*), and spectral power(*7*)} and the theta/alpha rhythm of EEG showed a higher degree of correlation with increasing number of dimensions. The beat-interval (*1*) can be regarded as the feature with the least influence on the R^2 value. The fact that the combinations of features with more than three dimensions have high R^2 values suggests that they can be used as indirect indicators to estimate the degree of attention of a subject under investigation.

ACKNOWLEDGMENT

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP; No. 2010-0026833).

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