Health Technol. (2012) 2:89–94
DOI 10.1007/s12553-011-0012-1

SHORT COMMUNICATION

Electrooculogram based study to assess the effects of prolonged eye fixation on autonomic responses and its possible implication in man-machine interface

Yogender Aggarwal · Nishant Singh · Rakesh Kumar Sinha

Received: 19 April 2011 / Accepted: 14 December 2011 / Published online: 29 December 2011

Abstract Need of an alternative method for communication has been seriously felt for man-machine interface (MMI) because of difficulties in the analysis of complex electroencephalogram (EEG). The proposed method analyses the alterations in autonomic responses due to prolonged eye gaze. The experimental paradigm was designed to include 20 trials of 30 s for eye gaze and 10 s for relaxation. Along with electrooculogram (EOG), electrocardiogram (ECG), pulse plethysmogram (PPG) and electrodermal activity (EDA) was recorded from the five male subjects. Results demonstrated that the eye gaze modulates heart rate, pulse rate and EDA signals that were too analyzed to occur with the latency of nearly 5 s, which is nearer to the EEG based brain-machine interfaces (BMI). The alterations in autonomic variables persist for longer duration and the maximum change in pulse rate was observed at 26.79 s (5.16 beats/minute) in comparison to the maximum change of heart rate (6.27 beats/minute) at 27.45 s, respectively. Further, the changes in EDA were found more at the onset of events. With the above findings, it can be suggested that the changes in autonomic responses with the mental effort produced by eye gaze were distinct and provides a good platform for the development of MMI.

Y. Aggarwal (✉) · N. Singh · R. K. Sinha
Department of Biomedical Instrumentation,
Birla Institute of Technology,
Mesra,
Ranchi, Jharkhand, India 835215
e-mail: yogender.aggarwal@gmail.com

N. Singh
e-mail: nishant22jan@gmail.com

R. K. Sinha
e-mail: rksinhares@gmail.com

Keywords Autonomic responses · Electrooculogram · Eye gaze · Man-machine interface

1 Introduction

Stroke is one of the largest killer identified in the human society. The impaired supply of oxygen and the communication breakdown from central nervous system (CNS) to the skeletal muscles are among the commonest indications of stroke. Some of the well known ailments, which have been resulted due to the stroke are, paraplegia, hemiplegia, tetraplegia and amyotrophic lateral sclerosis. In these pathological conditions, neuromuscular pathways are disrupted that leads to long-term motor disabilities. However, their sensorimotor cortices are activated during attempted movements. For such subjects to fulfill their day to day activities brain-machine interfaces (BMI) provide direct communication pathway between the brain and an external device to assist and augment the human sensorimotor functions [1–4].

So far, different techniques have been employed to implement BMIs [5–8]. However, the major difficulty lies in the method for extracting the features from acquired brain signals, which are highly non-stationary and uncomfortable to subjects due to the attached scalp electrodes. Recently, it has also been suggested that an alternative source of information can be identified from various other electrophysiological parameters. Apart from brain signals, electrooculogram (EOG) [9, 10] and autonomic variables [11–13] have also been used effectively for developing hybrid type of BMIs. It is generally understood that in most of the stroke cases, cognitive functions remains intact with capability of eye ball movements. Based on this hypothesis, Barea and coworkers [9] have developed the motorized wheel chair for disabled people, who could solely operate through the features extracted from the EOG. Further, Usakali et al., [10] also proposed the effective use of EOG in the development of man-machine interface (MMI). Though, the developments of assistive devices with EOG were more or less based on the gaze direction as well as on the controlled eye blink, the control of random eye movement is another challenging task.

Conversely, it is supposed that the unidirectional continuous eye fixation is enough to produce mental effort as it affects significantly the premotor cortex area [14]. It has been demonstrated that the activation of neurons in dorsal premotor area that encode the reach goal is relative to the eye fixation and irrespective of the hand position [15]. Simultaneously, these mental efforts may be able to produce autonomic activation similar to as demonstrated earlier [16]. Morata in 2005, confirmed that the mental efforts produced in their experiments modulated the autonomic responses [17], which were also considered as the components of the behavioral responses of CNS [18]. On the similar line of research in the area of BMI, researchers have already proposed the use of autonomic parameters in the development of command to control the external devices. However, no literature has been identified, which demonstrates the effects of eye gaze on autonomic responses.

Therefore, the aim of present study is to analyze the effects of mental effort produced by eye gaze on autonomic responses, so that the effects of eye gaze without any motor imagination (MI) on the autonomic variables can be evaluated for the ultimate target of proposal of new MMI system.

2 Materials and methods

Subjects and experimental paradigm This study involved five young male volunteers (S1 to S5, age 20–30 years and weight 55–65 kg) without any medical history. The experimental protocol was demonstrated to all the subjects and the consents were signed for their involvement in the study. The study was designed to record the lead-II electrocardiogram (ECG), pulse plethysmogram (PPG) and electrodermal activity (EDA) with EOG to observe the consistency of eye fixation. One animated power point presentation (Microsoft Office 2007, USA) was designed with 20 trials per subject. Each trial consists of 30 s eye gaze followed by 10 s relaxation period to the subject (Fig. 1). During the eye gaze period, a smiley appears at the center of the computer screen for 30 s. The subject was asked to gaze the smiley that constantly appeared on the computer screen. After the finish of gaze period, a star appears on the screen for 10 s to signal the subject to rest. During the relaxation period subjects were not advised to adopt a continuous eye closed condition, however, allowed for eye blink.

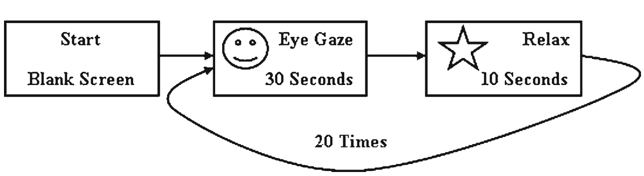


Fig. 1 The experimental paradigm used for the recording

Signal recording and processing With standard recording protocol, the biosignals (ECG, PPG, EDA and EOG) were recorded with the help of 4-channel bio-amplifier (Biopac Inc., USA) and Ag-AgCl disposable electrodes. Subjects were instructed to be seated on the armed rest chair and foot rested on insulated surface. Out of four, first channel was used for lead-II ECG, second for PPG, third for EDA and the fourth for EOG, and data were recorded as per the experimental paradigm. The PPG signal was recorded from distal phalanges of index finger of the left hand and EDA from proximal phalanges of the index and middle fingers of right hand of the subjects. For EOG, three electrodes were placed, one above the nasion, and two below the outer canthi of each eye, generating in a right-angled triangle (Fig. 2) as suggested by Scherer et al. [19]. All the digital recordings were performed with the sampling frequency of 200 Hz. The snapshot of the subject with all electrodes placed with running paradigm is shown in Fig. 3.

The mean heart rate and pulse rate changes across the trials were calculated over the paradigm period to confirm whether there occurred distinct variations in ECG and PPG during the eye gaze time. To analyze the heart and pulse rate variability, a methodology was adopted from Pfurtscheller et al. [11]. The R-wave of the ECGs and the peaks of pulse waves were identified and R-R and peak-to-peak intervals were calculated, respectively, with the help of software (Acknowledge 4.0, Biopac Inc. USA) using a modified Pan-Tompkins algorithm. The algorithm normalizes the wave data to 1 whereby the peak amplitude of the highest peak of the wave represents 1. The threshold level of 0.5 has been placed in the middle of the wave. The threshold level is used for the calculation of interpolated heart rate variability

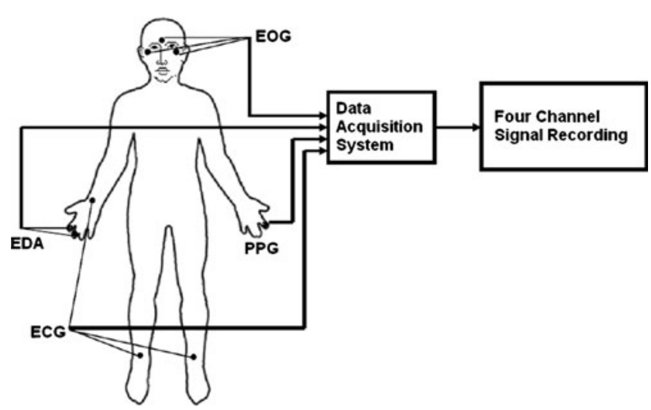


Fig. 2 Representative diagram of the electrode placement and recording setup

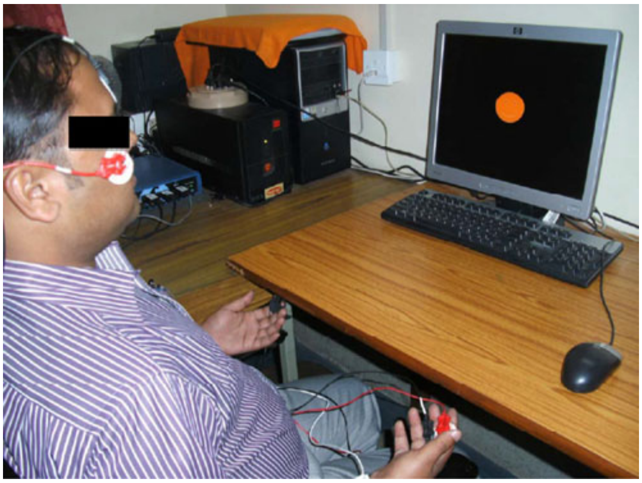


Fig. 3 Snapshot of running experimental paradigm with subject

(IHRV) and interpolated PPG (IPPG) from ECG and PPG signals at 8 Hz spline re-sampling frequency, respectively, by a cubic-spline interpolation method. The averaging was performed across 100 trials (from 5 subjects) obtained from all the five participants using MS Excel (Microsoft, Office 2007, USA). Further, to get the normalized variations, the relative changes in heart rate and pulse rate were calculated by subtracting the 5th digital value of each trial, respectively, in order to maintain the origin of each trial on the 5th data point as zero. The averaged and normalized data has been plotted for mean IHRV and mean IPPG analysis both for eye gaze (30 s) and relax condition (10 s). While on the other hand, before final calculation of average changes, EDA and EOG signals were band pass filtered at 0.01 to 0.5 Hz and 0.01 to 5 Hz frequency bands, respectively. The data of all 100 trails taken from all the subjects for EDA and EOG activity were taken to MS Excel Spreadsheet and mean for these parameters were calculated.

Statistical analysis All the statistical analyses were performed manually. Significance of changes in heart rate during relaxation and gaze period were calculated with the help of paired *t*-test. For the analysis, mean heart rate data of last 5 s of the eye gaze and relaxed condition were analyzed. Further, the Pearson's coefficient of correlation analysis (r) was also performed to evaluate the alterations in heart rate and EDA with eye gaze, if any, in these parameters. For the correlation analysis, mean data between 0–5 s, 25–30 s and 35–40 s (relaxation period) of the paradigm were considered. The brief description of the correlation analysis as described by Gupta [2000] is given below.

$$r = \frac{\sum xy}{\sqrt{\sum x^2 \times \sum y^2}}$$

The coefficient of correlation (r) is said to be a measure of covariance between two series. The covariance of two series X and Y is written as

$$Covariance = \frac{\sum xy}{N}$$

where, x and y stands for deviation of X and Y, respectively, from their respective mean.

$$x = \left(X - \overline{X}\right) \, and \, y = \left(Y - \overline{Y}\right)$$

3 Results

Analysis of autonomic responses With the analyzed EOG (Fig. 4) from 100 trials (*n*=5) of the assigned mental task through eye gaze and further relaxation period, a distinct alterations in recorded parameters have been observed. The analyses suggested distinct alterations in heart rate, pulse rate and EDA during eye fixation.

It has been observed that heart rate and pulse rate decreases during gaze period and tries to attain the baseline during relaxation condition (Fig. 5). Conversely, the analysis of the data of IHRV and IPPG shows reverse changes in comparison to their respective heart and pulse rate changes (Fig. 6). With the help of these results, remarkable and consistent increase in peak-peak interval has been revealed that also suggests the decrease in mean heart and pulse rate during the fixation period. Further, the time point for getting maximum difference in these two signals are almost same (27.45 s for ECG and 26.79 s for PPG) during the trials, the consistency of the variation was also observed very much similar in these two parameters. The mean pulse rate variability showed maximum rise at 26.79 s with a shift from the baseline of 5.16 beats/minute in comparison to the changes in heart rate, 6.27 beats/minute (Fig. 6). It is very important to analyze that the changes in EDA during the eye gaze and further in relaxation period follows the similar pattern as the

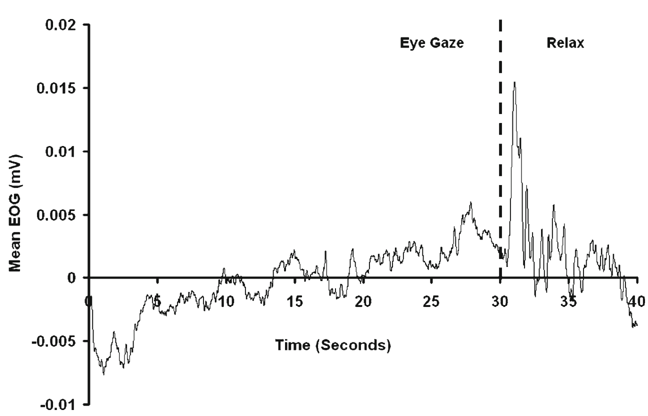


Fig. 4 Mean electrooculogram activity under eye gaze period of 30 s followed by 10 s eye relaxation period (5 subjects, 100 trials)

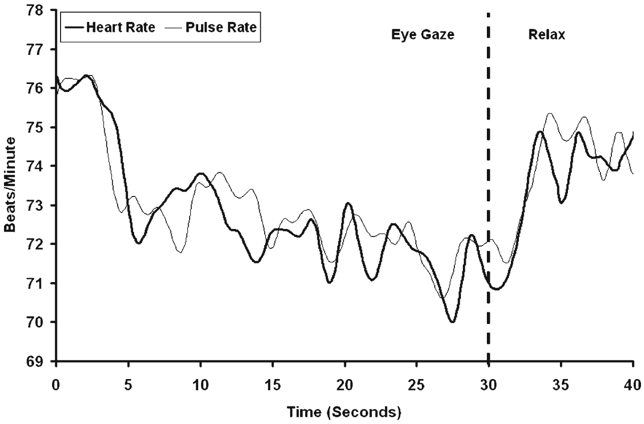


Fig. 5 Mean heart rate and pulse rate analysis under eye gaze period of 30 s followed by 10 s eye relaxation period (5 subjects, 100 trials)

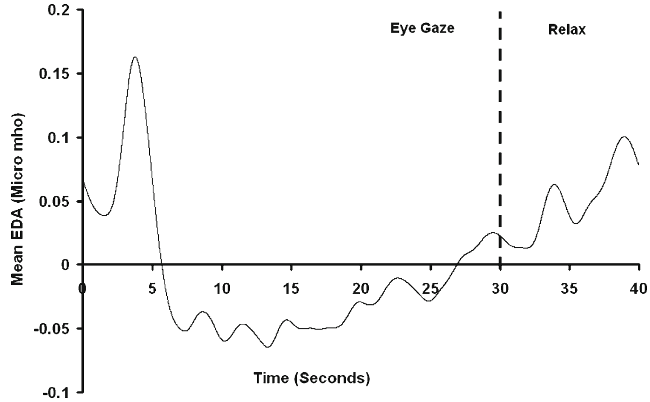


Fig. 7 Electrodermal activity produced due to prolonged eye gaze period of 30 s followed by 10 s eye relaxation period (5 subjects, 100 trials)

heart and pulse rate. However, this parameter shows sudden jump just after the onset of task and then slowly attain its initial position (Fig. 7).

Correlation analysis between autonomic parameters Based on these results, HRV during the maximum change period (25th to 30th s) and the last 5 s of relaxation period for all the 5 subjects was evaluated for the significance of alterations. With the paired *t*-test, changes between the mean values of heart rate for gaze and relaxation period were found to be significant (t=2.95, P<0.05). Subject wise as well as averaged heart rate changes have also been presented in Fig. 8.

The correlation analyses were performed between data sets of the heart rate and EDA. The time points selected for the evaluation were the first 5 s of the gaze period (within the latency period), last 5 s of eye gaze (maximum deviation period in the heart rate) and the last 5 s of the relaxation period. For each of the mentioned 5 s period, mean for heart rate and EDA for all the 5 subjects were calculated and taken for the correlation analysis. A positive correlation was analyzed between heart rate and EDA variations during the first 5 s of gaze duration (r=0.614) and the last 5 s of relaxation period (r=0.567), while negative correlation was calculated during the maximum deviation period of the heart rate of the gaze time (r=−0.194).

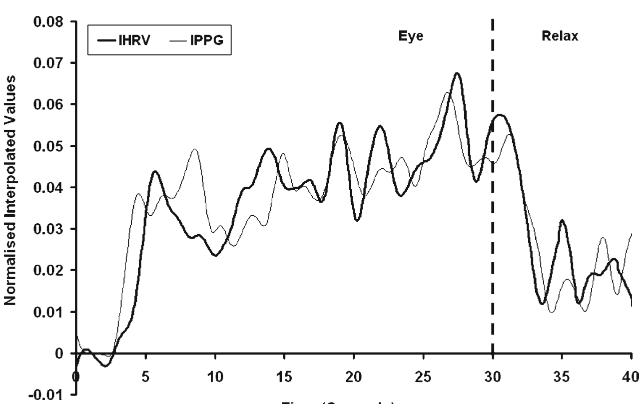
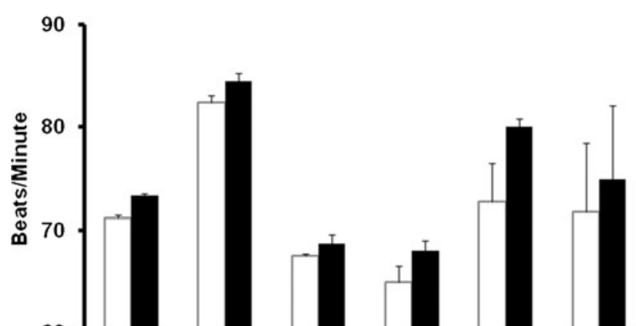


Fig. 6 Mean interpolated heart rate variability (IHRV) and interpolated pulse rate variability (IPPG) analysis under eye gaze period of 30 s followed by 10 s eye relaxation period (5 subjects, 100 trials)

4 Discussion

In the present work, effect of prolonged eye fixation on three parameters viz. heart rate, pulse rate and EDA have been evaluated. The observed results have shown the gradual decrease in heart rate and pulse rate during gaze period and tries to attain the baseline during relaxed condition. The consistency of the alterations was observed to be very much similar in these two parameters (Figs. 5 and 6). The statistical analyses also suggested a significant difference between heart rate at the time of eye fixation and relaxation (t=2.95, P<0.05). Considering the findings of this pilot experiment, it is understood that prolonged eye fixation



	S1	S2	S3	S4	S5	Average
□Gaze	71.15 ± 0.27	82.34 ± 0.70	67.46 ± 0.24	64.96 ± 1.54	72.73 ± 3.73	71.73 ± 6.67
■Relax	73.33 ± 0.22	84.42 ± 0.85	68.64 ± 0.94	67.98 ± 0.99	80.01 ± 0.81	74.88 ± 7.18

Fig. 8 Subject wise (20 trials) as well as mean±S.D. variations (5 subjects, 100 trials) of heart rate during the maximum deviation period (25th to 30th s) of eye gaze period and the last 5 s of eye relaxation period

certainly produce some mental effort that influences the autonomic nervous system to alter cardiac responses, which is similar to the past hypothesis [17]. The obtained findings were also found to be in accordance with the results and hypothesis as suggested by Pfurtscheller et al. [11] in which they demonstrated that decrease in heart rate with MI in a normal environment during preparation for a voluntary movement. However, in contradiction to above findings, Oishi et al. [16] suggested a significant increase in heart rate, but with different mental task.

As eye gaze being the first step in reaching the visual goal, the accurate goal-directed reach typically rely on the eye gaze and motor action [20]. On the other hand, it has been revealed that the unidirectional extended eye fixation is enough to produce the mental effort as it affects significantly the premotor cortex area [14]. Further, it has also been demonstrated that the activation of neurons in dorsal premotor area that encode the reach goal is relative to the eye fixation and irrespective of the hand position [15]. Therefore, the designed paradigm with constant fixation without any motor movement (or MI) to produce mental effort is justified. Further, Collet et al., [18] supported that the mental effort produced alterations in autonomic responses, which were also considered as the components of the behavioral responses of CNS.

The results indicate that there is covariance between measures of heart rate, pulse rate and EDA recorded during the eye gaze produced mental effort. The Pearson's correlation analyses suggested that deceleration of the heart rate is negatively correlated ($r=-0.194$) with the EDA at the peak of mental effort (25–30 s), otherwise it is positively correlated ($r=0.614$ at the start of mental effort and $r=0.567$ during the relaxation). Similar to the results obtained, literature has also revealed that in activation phase EDA increases and decreases in relaxed condition [18]. During the mental effort skin conductance level increases [16], which is measured as the function of activation of eccrine sweat glands those are innervated by the sympathetic chain of autonomic nervous system [21]. In the line of research hypothesis suggested by Oishi et al. [16], it can also be shown that when MI is performed, many physiological responses are activated, which may produce a low level efferent leakage effects on several autonomic variables [22]. The autonomic activation in this case is greater than the required during MI, occurs due to enhanced metabolic demand and have central origin [23, 24]. With these findings, it can be suggested that the prolonged eye gaze modulates both cardiac as well as eccrine system.

On the similar line of research in the area of BMI, researchers have already proposed the use of autonomic parameters in the development of command to control the external devices [13, 19]. However, no literature has been identified, which demonstrates the effect of prolonged eye gaze on autonomic responses. For the analysis of changes in autonomic variables, EOG signals have been considered as standard for the present experiment. It was identified that the EOG provides the standing corneal-retinal potential of the eye and proportional to the rotational angle of the eye [9, 25]. With the analyzed EOG from 100 trials of the assigned mental task through eye gaze and further relaxation period, a distinct variation in autonomic parameters have been observed, which can be useful for actuating a device for the purpose of MMI. Further, it was very interesting to note that the latency of changes (onset of response) in autonomic parameters lies nearly on 5th s of the start of trial, which is not far from the results obtained with the EEG data used for the BMI systems [26, 27].

5 Conclusion

The findings of the experiment suggest distinct changes in autonomic parameters such as ECG, PPG and EDA during the eye gaze trial. It was observed that the changes in these parameters start nearly on 5th s of the start of trial. It means the latency of separability between the eye gaze and relaxation are obtained just after 5 s of the trial, which is more or less similar with the results obtained with standard EEG data in BMI systems. Further, it is very interesting to note that the separability in these slow autonomic responses (ECG and PPG) with the relaxation persist for longer duration and reached on the maximum level between 25th to 30th s of the trial. Thus, it can be suggested that eye gaze modulated HRV provides better opportunity for the design and development of MMI in comparison to conventional BCI system.

Acknowledgement Authors gratefully acknowledge University Grants Commission, New Delhi, India for providing financial supports under Major Research Project (F.No. 36-60/2008 (SR)) to carry out this work.

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