Quantitative assessments of arousal by analyzing microsaccade rates and pupil fluctuations prior to slow eye movements

Shogo Honda[1], Takeshi Kohama[2], Tatsuro Tanaka[1] and Hisashi Yoshida[2]

***Abstract*— It is well known that a decline of arousal level causes of poor performance of movements or judgments. Our previous study indicates that microsaccade (MS) rates and pupil fluctuations change before slow eye movements (SEMs) (Honda et al. 2013). However, SEM detection of this study was obscure and insufficient. In this study, we propose a new SEM detection method and analyze MS rates and pupil fluctuations while subjects maintain their gaze on a target. We modified Shin et al.'s method, which is optimized for EOG (electrooculography) signals, to extract the period of sustaining SEMs using a general eye tracker. After SEM detection, we analyzed MS rates and pupil fluctuations prior to the initiation of SEMs. As a result, we were able to detect SEMs more precisely than in our previous study. Moreover, the results of eye movements and pupil fluctuations analyses show that gradual rise of MS rate and longitudinal miosis are observed prior to the initiation of SEMs, which is consistent with our previous study. These findings suggest that monitoring eye movements and pupil fluctuations may evaluate the arousal level more precisely. Further, we found that these tendencies become more significant when they are restricted to the initial SEMs.**

I. INTRODUCTION

It is well known that biomedical signals, such as EEGs (electroencephalogram), may be indicators of decline of arousal states. Monitoring techniques of arousal states may help to prevent accidents caused by human error. Nevertheless, recording of biomedical signals precisely in practical situations making use of application developments may become problematic because we need to wear measuring equipment. As the eyes can be recorded more easily than other biomedical signals, without making contact, they might be good candidates to observe arousal states.

In our previous study [1], we showed that several seconds before occurrence of slow eye movements (SEMs) [2], the rate of microsaccades, small and involuntary gaze shifts while fixating on a target, become higher and pupil diameters shrink persistently, which means that these signals may be adequate indicators to monitor arousal states. However, since the accuracy of SEM detection in this study was insufficient because of occasional half blinks, we need to detect SEMs more precisely.

In this study, we propose an SEM detection procedure based on Shin et al.'s method [3] to reexamine the transition of arousal level from the analyses of fixation eye movements and pupil fluctuations just before the occurrence of SEMs, while subjects maintain their gaze on a small fixation crosshair in a darkened room.

[1] S. Honda and T. Tanaka are with the Graduate School of Biology-Oriented Science and Technology, Kinki University, Wakayama, 649-6493, Japan. im3005hs at waka.kindai.ac.jp

[2] T. Kohama and H. Yoshida are with Faculty of Biology- Oriented Science and Technology, Kinki University, Wakayama, 649-6493, Japan. {kohama,yoshida} at info.waka.kindai.ac.jp

II. EXPERIMENTAL PROCEDURE

Subjects were instructed to maintain their gaze on a small crosshair fixation target presented at the center of a CRT screen and click on a mouse whenever they were aware of having slept in order to obtain the critical times of arousal breakdown. During the experiments, we recorded subjects' fixation eye movements and pupil diameters using HS-VET 250 Hz (Cambridge Research Systems). The sampling rate was 250 Hz and the maximum measurement time was 40 min. The accuracy of the equipment is high enough to detect microsaccades (MSs) having amplitudes which are larger than 1 deg. The viewing distance was 500 mm and the width and the height of the fixation target were both 1 deg. The subjects were three men (AE, MH, MY) in their twenties who have sufficient visual acuity to maintain their gaze on a fixation target, and got enough sleep the previous night.

III. ANALYSIS METHODS

A. SEM

SEMs are slow rotary motions of the eyes which are known to occur frequently during the wake-sleep transition [5] shown in Figure 1. According to this property, we can determine that decrement of arousal level reaches a limit from the time of occurrence of SEMs.

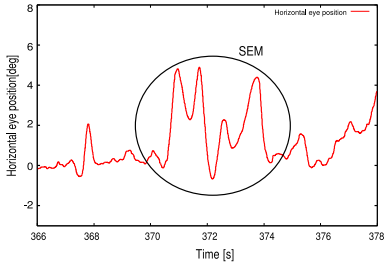

Fig. 1. Example of a waveform of SEM.

We proposed an SEM detection method based on the thresholding of the mean square of horizontal eye movements [1], whereas it was not adequately precise because of occasional half blinks which made the profile of fixation eye movement data analogous to SEMs.

By contrast, Shin et al. [4] indicate that the integrative analysis of amplitude and averaged velocity is effective to discriminate SEMs for every datum of each time period, at least for the horizontal EOG (electrooculography) data.

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However, since the spatial accuracy of our equipment is much higher than that of EOG, measured eye movement data are quite different from EOG, and Shin et al.'s method could not identify an SEM as a section which sustained for several seconds.

Here we propose a new SEM detection algorithm based on Shin et al.'s method. To simplify the procedure, we analyzed horizontal eye positions only. Fig. 2 shows our algorithm to detect SEMs, which is composed of six steps:

Step 1: Apply a 30 point moving-average window to horizontal eye movement data in order to attenuate noise.

Step 2: Apply a low-pass differentiation filter [8] to moving-averaged data to obtain eye velocity signals.

Step 3: Find zero-crossing points of velocity signals which means that the directions of movements have changed. Zero-crossing is defined by the following equation:

$$v(t-1) \cdot v(t) < 0, \tag{1}$$

where $v(t)$ is an eye velocity signal that was obtained from step 2 at time t.

Step 4: Calculate amplitude fluctuations $Za(t)$ and velocity fluctuations $Zv(t)$ between the pair of zero-crossing points. $Za(t)$ and $Zv(t)$ are defined as follows:

$$Za(t) = |em(t) - em(t_0)|, \tag{2}$$

$$Zv(t) = \frac{Za(t)}{t - t_0}, \tag{3}$$

where $em(t)$ is the horizontal eye position data, t_0 is the starting time of each zero-crossing point.

Step 5: Determine threshold values of $Za(t)$ and $Zv(t)$ respectively. Since SEMs are slow and large amplitude movements, SEMs are defined as points that fulfill the following conditions:

$$Za(t) > Za_{th}, Zv(t) < Zv_{th}, \tag{4}$$

Step 6: Count the numbers of detected SEMs inside a 5000 point moving-window, then apply a threshold to determine the sections of each SEM using the following equation:

$$\frac{1}{2N+1} \sum_{i=-N}^{N} SEM(t+i) > SEM_{th}, \tag{5}$$

where $SEM(t)$ is the detected SEM point for each N points window ($N = 5000$). The thresholds of $Za_{th}, Zv_{th}, SEM_{th}$ are decided as the most appropriate value for several subject. We defined the section of analysis of fixation eye movements and pupil fluctuations from 25 seconds to 5 seconds prior to the starting points of each SEM section.

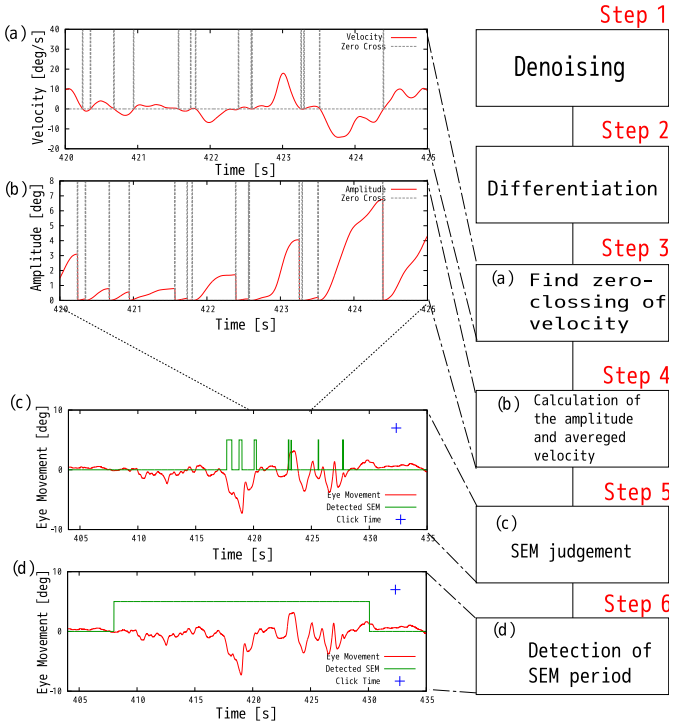

Fig. 2. Proposed SEM detection method based on Shin et al.'s method

B. Microsaccades

As a preprocessing of MS detection, we applied a median filter for noise reduction formulated as follows:

$$em_{med}(t) = \mathrm{Med}\left[em(t - \frac{k}{2}), \cdots, em(t), \cdots, em(t + \frac{k}{2})\right], \tag{6}$$

where $em_{med}(t)$ is the denoised data, and $\mathrm{Med}[\mathbf{x}]$ is the median of $\mathbf{x}$. The parameter k was set to 15 as a value that could detect MSs most exactly. Figure 3 shows an example of the results.

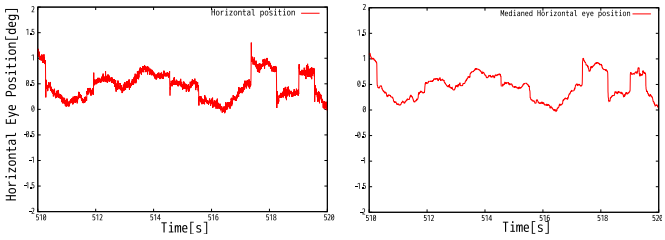

Fig. 3. Noise reduction by using a median filter.

Subsequently, we applied the low-pass differentiation filter to obtain velocity signals of eye movements. The low-pass differentiation filter is defined by:

$$em_{vel}(t) = \frac{SR}{N(N+1)} \sum_{n=1}^{N} \left[em_{med}(t+n) - em_{med}(t-n)\right], \tag{7}$$

where $em_{vel}(t)$ is the eye velocity signal, SR is the sampling rate (250 Hz), and the parameter N is set to 2. MSs were detected by thresholding the eye velocity signals. The threshold values were optimized for each subject. The number of detected MSs was counted in a moving-window, and the frequency of MSs in each window was computed by following equation:

$$MS_{rate}(t) = SR \cdot \frac{MS(t)}{2N_{ms}+1}, \tag{8}$$

where $MS(t)$ is the number of MSs and $MS_{rate}(t)$ is the frequency of MSs in each window of $2N_{ms}+1$ points. The parameter N_{ms} is set to 500.

C. Pupil fluctuation

For the analysis of the long-term pupil fluctuations, we adapted a linear regression method to the pupil diameter data $PD(t)$. The transition of regression coefficient $RC(t)$ was obtained by the following formulas:

$$RC(t) = \frac{M\sum_n W_n(t)\cdot PD(t+n) - \sum_n W_n(t)\sum_n PD(t+n)}{\sum_n W_n(t)^2 - \left[\sum_n W_n(t)\right]^2},$$
$$M = 2N_{pd}+1,$$
$$W_n(t) = t+n-t_k, \tag{9}$$

where t_k is the starting point of kth window, $N_{pd} = 2500$ and $-N_{pd} \le n \le N_{pd}$. A typical example of pupil diameter and RC are shown in Figure 4.

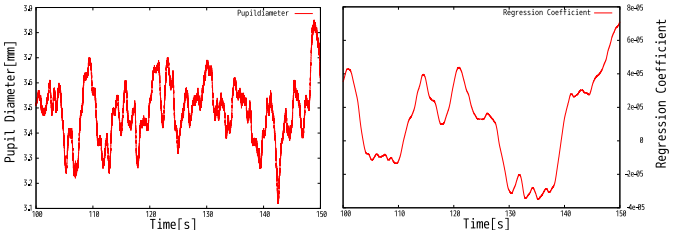

Fig. 4. Example of transition of pupil diameter and its RC.

D. Arousal Section

In order to compare MSs and pupil fluctuations in arousal states, 12 analyzing sections, 4 sections for all three subjects, were selected randomly from the data well before the first SEMs and adapted the same analyses.

IV. RESULTS

The total number of detected SEMs was 16 (Subject MH: 5, MY: 4, AE: 7). Figure 5 shows examples of horizontal fixation eye movements containing an SEM section. Vertical bars indicate mouse clicked time. As shown in this figure, almost all SEMs occurred just before mouse clicks, which

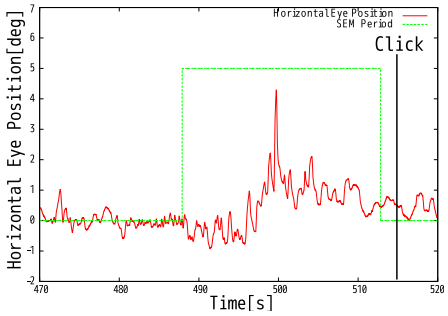

Fig. 5. Example of detected SEM periods with the time of mouse clicks.

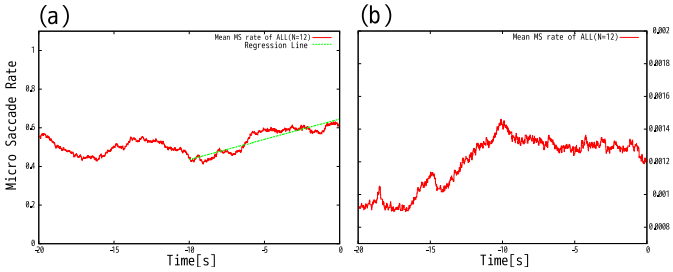

Fig. 6. (a) Ensemble average of $MS_{rate}(t)$ in analyzing section. (b) Ensemble average of $MS_{rate}(t)$ of arousal section.

means that SEMs always appear prior to the time when subjects were aware of having slept.

To examine the accuracy of SEM section detection, the start and end point of each SEM section were determined subjectively by six students in our laboratory for the use as a gold standard, which was computed by averaging them. The errors of the start and end points from the gold standard were -2.3 sec and 3.2 sec respectively. This suggests that the accuracy of proposed method to detect an SEM as a section is sufficiently high to analyze MS rates and pupil fluctuations prior to the initiation of SEMs.

We used from the first to the fourth SEM sections for each subject. As the tendency of MSs or pupil fluctuations in each analyzing section for each subject was roughly similar, we analysed them all together.

The ensemble average of $MS_{rate}(t)$ in the all analyzing section is shown in Figure 6 (a). The zero point of x-axis corresponds to the starting point of an SEM section. Note that the maximum value of each $MS_{rate}(t)$ was normalized to 1 before averaging. As well as our previous study, MS_{rate} has a tendency to increasing prior to the initiation of SEM sections. This means that the MS rate increases toward the initiation of SEM period. We calculated a correlation coefficient of the MS_{rate} for 10 seconds prior to the SEMs. As a result, there was a positive correlation (t-test: $p < 0.01$).

Figure 6 (b) shows averaged MS_{rate} in arousal sections. Each MS_{rate} in an arousal section was normalized by max value of MS_{rate} before the first SEM section. As shown in Figure 6 (b) , the averaged MS_{rate} is almost zero in the arousal sections. This indicates that MSs rarely occur in the arousal state and MS rate is gradually biased as arousal level declines.

Figure 7 (a) shows the ensemble average of $RC(t)$ dur-

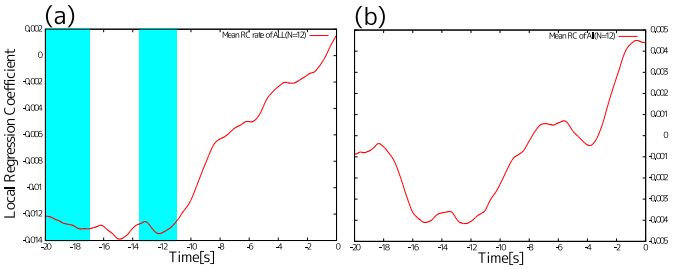

Fig. 7. (a) Ensemble average of $RC(t)$ in analysis section, (b) Ensemble average of $RC(t)$ in arousal section.

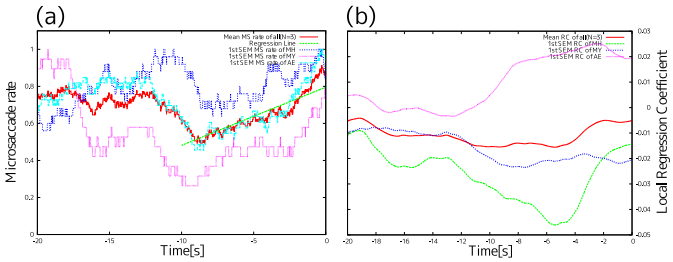

Fig. 8. Ensemble average of $MS_{rate}(t)$ and RC in analysis section of the first SEM.

ing the section of analysis. The zero point of the x-axis corresponds to the starting point of an SEM section. The regression coefficient has negative value from 20 seconds to 1.5 seconds before initiation of SEMs. This indicates that there is a persistent tendency of miosis prior to around over 20 seconds the occurrence of SEMs. The filled areas in Figure7 (a) indicate that the averaged $RC(t)$ is significantly lower than 0 (t-test : $p < 0.05$). The averaged $RC(t)$ during arousal sections is shown in Figure 7 (b). It fluctuates considerably among negative and positive values unlike the tendency of the analysis sections.

V. DISCUSSION

It is considered that the subjects were aware of brief loss of consciousness when they clicked the mouse button. Therefore, the SEM periods preceding several seconds before mouse clicks obviously indicate that the decline of arousal level had reached the lower limit. The results of accuracy estimation of SEM detection indicate that the proposed method has errors of several seconds which include actual SEMs. If we regard these errors as safety margins, our method is sufficiently accurate to detect SEMs with certain duration.

Figure 6 (a) indicates that $MS_{rate}(t)$ significantly increased several seconds before SEM initiation ($\alpha = 0.65$, t-test: $p < 0.005$). By comparing the results in Figure 6 (a) and Figure 6 (b), we found that the averaged MS_{rate} of arousal sections is extremely lower than that of analysis sections. This suggests that there exists increasing bias of the MS rate in connection with decline of arousal level at least about 20 seconds before the initiation of SEMs. It is well known that the neuron networks which control fixation eye movements have a strong relationship with the visual attention networks. Since there is a correlation between focal attention and arousal states [6][7], our findings suggest that the top-down attention might be modulated by arousal states.

In Figure 7 (a) , the transition of $RC(t)$ showed negative values before the several ten seconds from initiation of SEM period. This suggests that long-term miosis is caused by decrease of arousal level. On the other hand, RC of arousal section has a consistent tendency.

It is known that eye movements are dominated by the central nervous system and transition of pupil diameter is dominated by autonomic nervous system. Our findings suggest that the decline of arousal level could be estimated well before the subjects realized it by monitoring eye movements and pupil fluctuations simultaneously.

Furthermore, we analyzed the $MS_{rate}(t)$ of analysis section restricted to the first SEM for each subject. Figure 8 (a) shows that there is a strong positive correlation just before the initiation of SEMs ($\alpha = 0.80$, t-test:$p < 0.005$). In addition, $RC(t)$ before the first SEMs have a smaller value for two of three subjects than the averaged $RC(t)$ (Figure 8 (b)). We are now constructing experiments to analyze eye movements and pupil fluctuations only before the first SEMs to verify if we can find a clearer tendency for predicting arousal breakdown under this condition.

VI. CONCLUSION

In this study, we proposed a new SEM detection method and analyzed MS rate and pupil fluctuations while subjects maintain their gaze on a target. As a result, we were able to detect SEMs more precisely than in our previous study [1]. Moreover, the results of eye movements and pupil fluctuations analyses show that gradual rise of MS rate and longitudinal miosis are observed prior to the initiation of SEMs, which is consistent with our previous study. Further, we found that these phenomenon become more significant when they are restricted to the first SEMs. These findings suggest that monitoring eye movements and pupil fluctuations may evaluate the arousal level more precisely.

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