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Quantitative evaluation of arousal level based on the analyses of microsaccade rates and pupil fluctuations

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Abstract— **In this study, we proposed an objective estimation of decline of arousal level by analyzing microsaccade rate and pupil fluctuation while subjects were continuously gazing a fixation target. Previous studies show that the slow eye movements (SEMs) could be a candidate for an indicator of decline of arousal. However, it is not sufficient to evaluate transition of arousal states since SEMs appear just prior to sleep onset. To establish more objective assessment of arousal, we examined the effects of the transition of arousal on microsaccade rate and pupil fluctuation. The subjects were instructed to indicate by mouse clicks when they were aware of having slept. We have analyzed the eye movement and pupil fluctuation data in advance of the occurrence of SEMs which were detected just before the mouse clicks. In the results, longitudinal pupil diameter shrinking and gradual rise of microsaccade rate were observed prior to SEMs. These results suggest that the arousal level could be evaluated by monitoring eye movements and pupil fluctuations.**

I. INTRODUCTION

The decrement of arousal level while driving cars or visual display terminal works would cause behavioral errors, so-called human errors, and sometimes lead serious accidents. Previous studies have applied the biomedical signals such as brain waves, body temperatures, heartbeats, skin electric potentials, and so on as the indexes of the arousal. Nevertheless, the quantitative evaluation of the declining arousal level is still difficult because of the poor knowledge of our behavioral transitions associate with the decline of arousal states.

Sakai et al.[1] have shown that reaction times for an auditory simulation significantly increased before appearance of slow eye movements (SEMs), which occur frequently while falling asleep. Another study have indicated that SEMs could be a candidate for an indicator of decline of arousal[2][3]. However, since SEMs appear just prior to sleep onset, it is not sufficient to evaluate transition of arousal states.

Involuntary eye movements during fixation has been thought as a ocular cramp, but recent studies indicate that the properties of fixation eye movements are modulated by allocation of visual attention[4]. It was shown that the frequency of microsaccades (MS), which are small jumps of fixation eye movements, decreases when visual attention is concentrated in the foveal region[5]. In an attentive fixation condition, the central nervous system must continue to directing visual attention to the fixation target while maintaining the eyes on the target. Since the arousal system affects the top-down attention control[6][7], transition of arousal level might influence the occurence of MS.

Pupil diameter fluctuations are closely related to the autonomic nervous system. The pupil diameter enlarges when the sympathetic nerve is dominant and contracts when the parasympathetic nerve is dominant. Wilhelm et al. have shown that the reductions of arousal level were associated with decreases of activity of the sympathetic nervous system and made the pupil diameter size small[8]. Therefore, the transition of arousal level might also affect the pupil diameter fluctuations.

The purpose of this study is to estimate the transition of arousal level from the analyses of fixation eye movements and pupil fluctuations just before the initiation of SEMs, while subjects continuously maintain their eyes on a small fixation target crosshair. In this paper, we analyzed the frequency of MS (MS rate) and longitudinal pupil diameter transition as indexes of subjects' arousal states. From experimental results, we demonstrate that MS rate and pupil fluctuations are both affected by lowering arousal level just before appearance of SEMs.

II. EXPERIMENTAL PROCEDURE

Subjects were instructed to maintain their gaze on the small crosshair fixation target presented at the center of the CRT screen and press mouse button whenever they had been 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 by using HS-VET 250 Hz (Cambridge Research Systems) the measuring method of which bases on video tracking of pupil and dual first purkinje images. The sampling rate was 250Hz and maximum measurement time was 40 min. The viewing distance was 500 mm and the width and the height of the fixation target was 1 deg respectively. The subjects were four men in their twenties who have enough visual acuity to maintain their gaze on the fixation target.

III. ANALYSIS METHODS

A. Microsaccades

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

$$em_{med}(t) = \mathrm{Med}\left[em(t-\frac{k}{2}),\cdots,em(t),\cdots,em(t+\frac{k}{2})\right], \quad (1)$$

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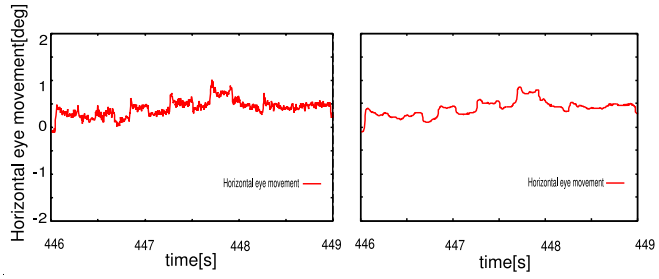


Fig. 1. Noise reduction by using a median filter.

where $em(t)$ is the original horizontal eye movement data, $em_{med}(t)$ is the denoised data, and Med[$\mathbf{x}$] is a median of $\mathbf{x}$. The parameter k was set to 15 as a value that could detect MS most exactly. Figure 1 shows a preprocessing result.

Subsequently, we applied low-pass differentiation filter[9] to obtain velocity signals of eye movements. The low-pass differentiation filter is defined by

$$em_{vel}(t) = \frac{SR}{N(N+1)} \sum_{n=1}^{N} \left[em_{med}(t+n) - em_{med}(t-n) \right], \quad (2)$$

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

$$MS_{rate}(t) = SR \cdot \frac{MS(t)}{2N_{ms}+1}, \quad (3)$$

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

B. Pupil fluctuation

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

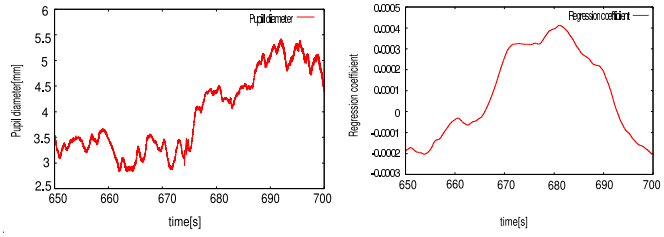


Fig. 2. A sample of transition of pupil diameter and RC

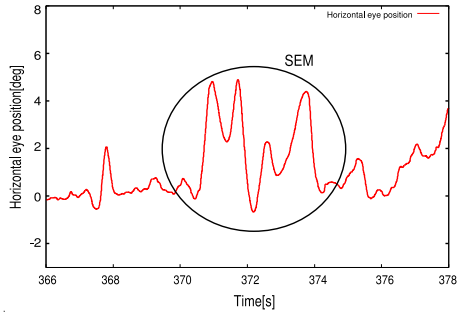


Fig. 3. A sample of a waveform of SEM.

$$M = 2N_{pd} + 1, \quad (4)$$

$$W_n(t) = t + n - t_k, \quad (5)$$

$$RC(t) = \frac{M \sum_n W_n(t) \cdot PD(t+n) - \sum_n W_n(t) \sum_n PD(t+n)}{\sum_n W_n(t)^2 - \left[\sum_n W_n(t) \right]^2}, \quad (6)$$

where t_k is time of starting point of window, $N_{pd} = 2500$ and $-N_{pd} \leq n \leq N_{pd}$. A typical example of pupil diameter and RC are shown in Figure 2.

C. SEM

SEM is a slow rotary motion of the eye which is known to occur frequently during the wake-sleep transition shown in Figure 3. According to this property, we can discriminate that decrement of arousal level reaches to the limit from the time of occurrence of SEMs, namely, SEMs can be objective indexes for estimating sleep onset. An SEM detection method has been proposed by Magosso et al.[10] for EOG data. However, since our equipment is highly accurate and measured eye movement data is quite different from EOG, we could not apply Magosso et al.'s method. Here we propose a new SEM detection method based on the mean square of eye movement in a certain period of time. The mean square of horizontal eye movement $X(t)$ is defined by,

$$X(t) = \frac{1}{2N_{sem}+1} \sum_n em^2(t+n), \quad (7)$$

where $N_{sem} = 500$ and $-N_{sem} \leq n \leq N_{sem}$. Then, the moving average and the standard deviation of $X(t)$ were calculated for each window by following formulas,

$$MA(t) = \frac{1}{2N_{ma}+1} \sum_n X(t+n), \quad (8)$$

$$\sigma(t) = \sqrt{\frac{1}{2N_{ma}+1} \sum_n \left[X(t+n) - MA(t) \right]^2}, \quad (9)$$

where $N_{ma} = 500$ and $-N_{ma} \leq n \leq N_{ma}$. A dynamic threshold $MT(t)$ for the use of discrimination of SEMs was defined as

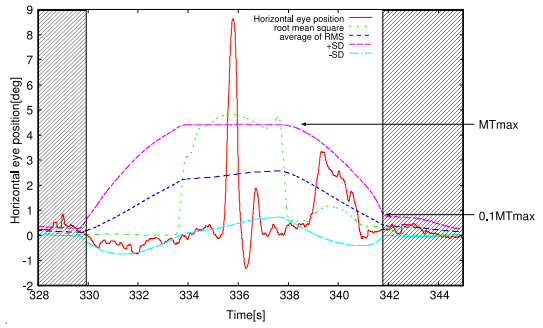


Fig. 4. Definition of SEM period.

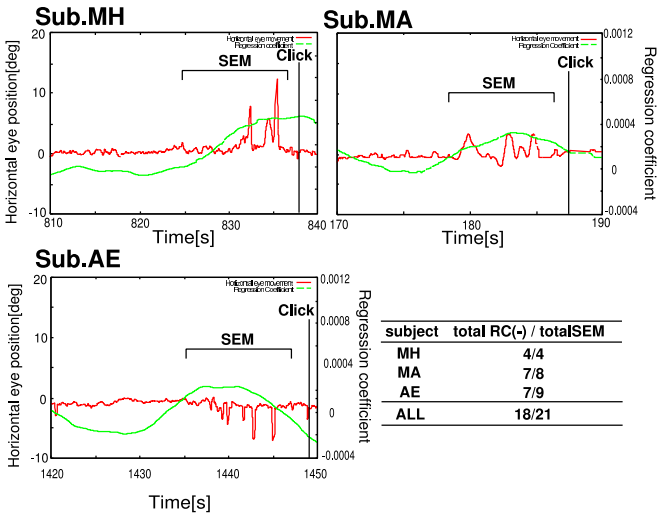
$$MT(t) = MA(t) + \sigma(t). \tag{10}$$

In Figure 4, $X(t)$ is depicted as a dotted green line and $MT(t)$ is depicted as dashed purple line.

Around the interval between the points where $X(t)$ crosses with $MT(t)$, we defined SEM period between the points where $MT(t)$ decreases 10% of maximum of $MT(t)$, which is depicted in Figure 4. We defined the analyzing period of fixation eye movements and pupil fluctuations from 20 seconds to 5 seconds prior to SEM period.

IV. RESULTS

SEMs were detected in three of four subjects (MH, MA and AE). The total number of SEMs for these three subjects was 21 times. Figure 5 shows examples of clicking time, indicated by vertical bars, and horizontal fixation eye movements (red line) containing a SEM period with $RC(t)$ of pupil fluctuations (green line). We can see that the SEMs occurred just before mouse clicks. It means that SEMs always appear prior to the time when the subjects are aware of having slept. Furthermore, $RC(t)$s have negative values just before SEM period showing the pupil diameter contraction. The ratios of $RC(t)$ which has negative values



subject	total RC(-) / totalSEM
MH	4/4
MA	7/8
AE	7/9
ALL	18/21

Fig. 5. SEM periods and pupil diameter transitions with the time of mouse clicks.

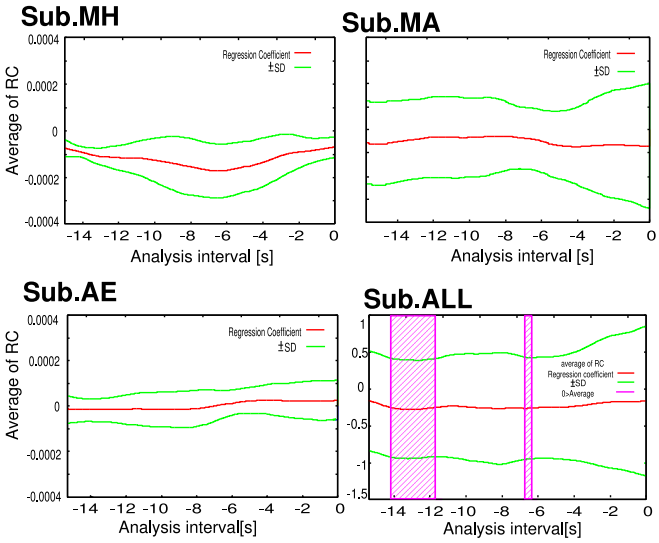


Fig. 6. Ensemble average and standard deviation of $RC(t)$.

to the number of all analyzing periods for each subject are shown in the table at the bottom right panel of the Figure 5.

Figure 6 indicates the ensemble average of $RC(t)$ during analyzing interval for these three subjects. The zero point of x-axis corresponds to the 5 seconds before the initiation of a SEM period. ALL means the average among all subjects. The shaded areas indicate the ensemble average of which are significantly less than 0 (t-test: $p < 0.05$). Note that t-test was performed under the condition that the minimum value of each ensemble of $RC(t)$ was normalized to -1 and averaged among all subjects. This result suggests that longitudinal miosis exists around ten seconds before the initiation of SEM period.

Figure 7 shows an example of eye movement in which the frequency of MS rapidly increases prior to the initiation of a SEM period. The ellipse indicates a section in which MS occurred at high frequency. The ensemble average of $MS_{rate}(t)$ for each subject (MH, MA and AE) in the analysis section is shown in Figure 8. Common to these subjects, MS_{rate} has a tendency to increase prior to the initiation of SEM period. We compared the median at the points $t = -1.5$s and $t = -3.5$s of the ensemble average

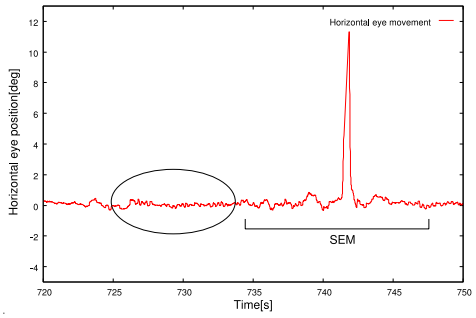


Fig. 7. An example of increasing MS prior to the initiation of an SEM period.

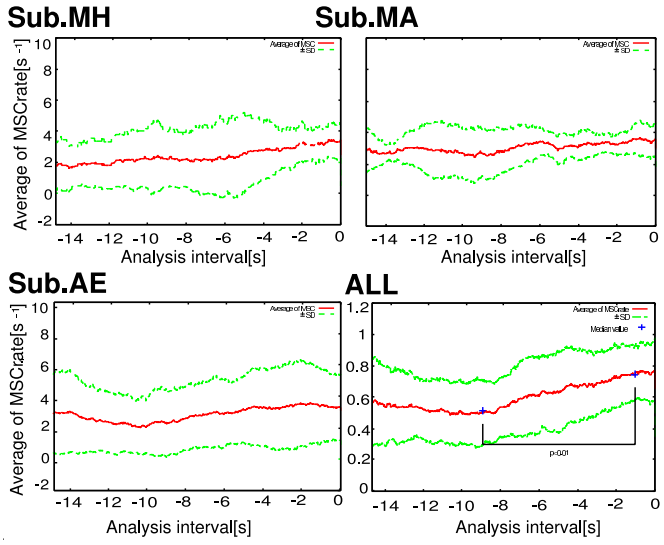


Fig. 8. Ensemble average and standard deviation of $MS_{rate}(t)$.

of $MS_{rate}(t)$ among all subjects. As a result, we found that the frequency of MS at $t = -1.5$s is significantly higher than that of at $t = -3.5$s (Wilcoxon-test: $p < 0.01$). This means that the MS rate increases toward the initiation of SEM period. Note that Wilcoxon-test was performed under the condition that the maximum value of each $MS_{rate}(t)$ was normalized to 1.

These tendencies were not observed at a few minutes after the experiments start.

On the other hand, small SEMs that did not exceed the detection threshold defined in this study were found in the data of subject FI in which mouse clicks had not occurred. The ellipse in Figure 9 indicates an SEM-like pattern. We applied our analyses to these small SEM-like pattern and found that $MS_{rate}(t)$ (red line) and $RC(t)$ (green line) showed similar characteristic like other three subjects.

V. DISCUSSION

It is considered that the subjects realized brief loss of consciousness when they clicked mouse-button following the SEM periods. The SEM periods preceding several seconds

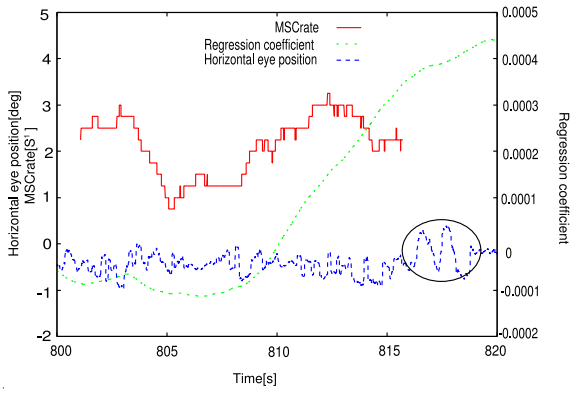


Fig. 9. Results of subject FI.

before mouse clicks obviously indicate that the decline of arousal level had reached the lower limit.

In the 18 samples, which corresponds to 85% of all SEMs, the transition of $RC(t)$ showed negative values several seconds before initiation of SEM period. This suggests that the long-term miosis is caused by decrease of arousal level.

Moreover, Figure 8 showed that $MS_{rate}(t)$ significantly increased several seconds before SEM initiation. Even in the eye movements of the subject who showed no SEMs and no mouse-clicks during whole experiments contained small SEM-like pattern, and increased frequency of MS. Also shrinkage of pupil diameter was found prior to this SEM-like pattern. These tendencies suggest that the decline of arousal level could be estimated well before the subject realized the declination of arousal. It is known that eye movements are dominated by the central nervous system and transition of pupil diameter is dominated by autonomic nervous system. Therefore, the transition of arousal level might predict more precisely by monitoring these signals simultaneously.

VI. CONCLUSION

In this study, we examine the effects of the transition of arousal on MS rate and pupil fluctuation while subjects are continuously gazing a fixation crosshair. As a result, as SEM approached, MS tended to increase and pupil diameter tended to decrease on a long-term basis before SEM. These results suggest we can estimate decline of arousal level that can't realize sleepiness by monitoring MS and pupil diameter. The results show that longitudinal miosis and gradual rise of MS rate are observed prior to the initiation of SEMs. This suggests that monitoring eye movements and pupil fluctuations could evaluate the arousal level more precisely.

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