Measurement of Fatigue Based on Changes in Eye Movement during Gaze

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SUMMARY We measured eye movements at gaze points while subjects performed calculation tasks and examined the relationship between the eye movements and fatigue and/or internal state of a subject by tasks. It was suggested that fatigue and/or internal state of a subject affected eye movements at gaze points and that we could measure them using eye movements at gaze points in real time.

key words: eye movement, fatigue, critical fusion frequency (CFF), calculation task

1. Introduction

In recent years, many sensing technologies have been studied for use in wearable terminals, automatic driving, and other applications. As an example, sensing technology is used in drowsiness detection systems applied during driving to measure the heart rate and brain waves [1] and in facial expression recognition systems [2] to detect fatigue states. The expression of the eyes is used in daily life as an indicator of a person’s feelings and physical condition. Mizushima et al. reported that the amplitude of small saccades generated during task execution may be used as a parameter for psychological stress [3]. Also, Wakui et al. indicated that the arousal state of humans is sensitively reflected in the pupil size and various eye movements (saccade, vestibulo-ocular reflex, vergence eye movement, etc.), and these parameters can be applied to measure the arousal state of humans [4]. Kohama et al. reported that the quantitative measurement of visual attention was possible using the characteristics of microsaccades [5], because the visual attention was observed to influence microsaccades. Therefore, we focused on eye movements at the gaze and conducted experiments considering whether it is possible to evaluate the degree of awareness and concentration during driving using a drive simulator in real time [6]. Our eyes do not stop even when we are gazing at a point. This movement known as small involuntary eye movements. These movements are often divided into three types, including relatively large and fast microsaccades, large and slow drifts, and small and high frequency tremors [7]. Among these movements, the microsaccade component in particular has been reported to change to reflect a person’s psychological state [8]. For these reasons, it is assumed that unconscious changes in a person’s internal state will be reflected in small involuntary eye movements. In addition, our experiments using drive simulator presented that the standard deviation of eye movement at the gaze points changes before and after passing a traffic sign [9]. However, a subject’s head was fixed by the head-chin rest to measure the small involuntary eye movements accurately in these studies and the only eye movements were measured. It is desirable to measure fatigue more naturally without fixing the head movements during work in real time. Therefore, in this article, we measured the eye movements at the gaze points without fixing the head movements while the subjects performed calculation tasks and examined the relationship between the eye movements and the critical fusion frequency (CFF) which was used as an indicator of fatigue. As a result, it was shown that the change in the eye movements is an effective parameter with which to measure the levels of fatigue and concentration.

2. Experiment

As the fatigue task, the subject performed a simple calculation task for 90 min, and the eye movements during the task were measured using a wearable eye movement measurement device. In addition, we measured CFF, which is commonly used as a fatigue indication, before and after the experiment. This experiment was conducted in accordance with the Tokai University ethical code on human experiments. The experiment flow chart is shown in Fig. 1. 10 students (7 males and 3 females, 20–24 years old) participated.

2.1 Calculation Task

In previous research, we used a reading task [10], we found that results depended to some extent on the participants reading habits. Therefore, we changed this to a simpler calculation task that lasted for 90 min, with a 3 min break at the 45 min mark. Subjects carried out addition lined up by sum up one digit number. The subject was in-
structured to perform the calculation as accurately and quickly as possible. A notebook PC (Sony Corporation, VAIO Duo 13) was used to display the calculation sheets. The calculation task was carried out by touch operation and consisted of the addition of single-digit random numbers arranged in two cells vertically in Excel. An example of the task is shown in Fig. 2.

2.2 Eye Movement Measurement

The EMR-8b (Nac Image Technology, Inc., Tokyo) which uses the pupil/corneal reflection method for eye movement detection was used for the measurement of eye and its detection rate is 60 Hz. We used the definition in which a gaze point was defined as occurring when the eye movement speed was less than 10 deg/sec and the gazing time was longer than 150 ms [11]. In this experiment, a subject’s head was not fixed during the task. Therefore the small movement to compensate for head movement is included in eye movement in a gaze point. When considering that one of the objects is the fatigue measurement while driving, the experiment which does not fix the head is desirable. Therefore, we had a subject do a calculation without fixing the head. The dominant eye was measured in the experiment.

2.3 CFF Measurement

CFF is a higher-order visual characteristic that involves the cerebrum, is effective for measuring mental fatigue, and is widely used conventionally. CFF decreases with increasing fatigue. A reduction in CFF not only indicates peripheral fatigue but also is considered useful as a judgment index of central fatigue [12]. To measure CFF, we used a flicker-measuring instrument (Takei Scientific Instruments Co. Ltd. Flicker value measuring instrument type II). The maximum frequency at which the flicker was detected by blinking the light slower or faster was used as the CFF. These methods were carried out five times, and the average value obtained was considered the CFF value.

3. Results and Discussion

3.1 Result of CFF

Table 1 shows the average of CFF before and after the task and result of paired t-test. CFF significantly decreased in 6 of 10 subjects in bold type ($p < 0.01$). As a result, CFF of all subjects were reduced due to performing the calculation task for 90 min. Therefore, we concluded that the calculation task showed a tendency to cause mental fatigue.

3.2 Result of the Calculation Task

The subject’s calculation task was recorded with the field of view camera (EMR-8b) to check the operation mistakes. Figure 3 shows the number of answers and the number of incorrect answers for subjects who performed the task for 90 min. There were variations among subjects. They answered about 3000 questions on average. In addition, the number of incorrect answers was about 30 questions, except or subject A, including operation mistakes on the touch panel. The reason the number of incorrect answers was large in subject A is the decrease in CFF is the largest from the results in Table 1, which presumed to be due to this subject feeling a fatigue strongly. Also, although the rate of incorrect answers is not more larger than subject A, similar trend was seen in subject B whose CFF value decreased 6.8% and in subject C whose CFF value decreased 7%. As the above, it is presumed that fatigue has influenced the rate of incorrect answers, and we assumed subject A and B were especially tired. However, the total number of answers that varied from subject to subject did not correlate with the level of fatigue. In other words, the total number of answers varies depending on the calculation skill of each subject, so it is difficult to compare them. It can be said that fatigue may
affect the rate of wrong from the results of subject A and B, because the rate of wrong of subject C is as low as other subjects.

3.3 Result of Eye Movements

In subject H, eye movement data did not measure well for 10 to 25 minutes. Additionally, it was difficult to analyze the video data of subject C during the experiment because it was damaged. Therefore, 2 of the 10 subjects were excluded from eye movement analysis. The standard deviation of eye movements at gaze points was calculated based on the movements within each gaze in real time. To carry out a real time analysis of changes in eye movements during a calculation task, we examined the horizontal and vertical components average standard deviation of eye movement at gaze points every 5 min during the task. Let us now consider the changes in the standard deviation every five minutes in subjects A and B, who were assumed to be tired since their CFF values decreased notably, as described in Chapter 3.2. The average horizontal and vertical standard deviations for subjects A and B are shown in Figs. 4 (a) and 4 (b), respectively. The horizontal component showed no large changes, while the vertical component rose sharply after 45 min and then decreased gradually to the end of task in subject B. In subject A, the horizontal component showed an upward trend at the beginning of the experiment, then decreased from 25 min until 55 min, increased to a high at 75 min, and finally decreased towards the end. His vertical component decreased initially until 30 min, increased until 60 min, decreased until 10 min before the end, and rose a little at the very end. Next, we examined the correlation between the number of answers and the standard deviation of eye movements during gaze points. We found that 4 of the 8 subjects (A, B, E, G) showed a significant correlation between ‘horizontal or vertical eye movements’ and the number of answers. In subjects A and B (Figs. 4 (a) and (b), respectively) there was a significant positive correlation between the number of answers and the vertical component of eye movement during gaze (p < 0.01). The horizontal and vertical components of subject B showed the same tendency in the first half of the task, as shown in Fig. 4 (b), however the number of answers and the vertical components of eye movements increased after 45 minutes. This result is thought to be due to a 3 minute break at 45 minutes. In subject E, in Fig. 4 (c), there was a significant negative correlation between the number of answers and the horizontal components of eye movements during gaze (p < 0.05). Subject E’s horizontal and vertical components of eye movement showed the same tendency as those of subject B in the first half of the task, after which the horizontal and vertical components of eye movements decreased. In subject G in Fig. 4 (d), there was a significant positive correlation between the number of answers and the horizontal components of eye movements during gaze (p < 0.05). The results of the remaining subjects (D, F, I, J) showed no significant correlation between the number of answers and the horizontal or vertical com-

![Fig. 4](image-url) The standard deviation of eye movements every 5 minutes during calculation task of four subjects (*) p < 0.05)
ponents of eye movements during gaze. Next, changes in the standard deviation of eye movements are compared before and after the task, as in CFF, and are shown in Fig. 5. We focused on the results of 4 subjects (A, B, E, G) who showed a significant correlation between “horizontal or vertical eye movements” every 5 minutes and the number of answers. When comparing the first and last 10 min, only subject G showed the same tendency of the correlation between changes in the standard deviation of eye movements and number of answers every 5 minutes. The same correlation was not observed for the other subjects including for subject A, B, and E. We will continue to examine whether this is due to individual differences depending on how to solve the calculation.

3.4 Discussion of Eye Movements

The eye movements during gaze between the vertical and horizontal components were examined by multiple comparisons of data obtained every 5 minutes using the Steel-Dwass method. The results of 4 subjects are shown in Figs. 4 (a)–(d). The green and blue arrows indicate the intervals during which significant differences (*: p < 0.05) were frequently obtained between the vertical and horizontal standard deviation, respectively, every 5 minutes. Let us consider the results of subjects A and B, who were assumed to be tired, as described in Chapter 3.2. In subject A, significant differences were observed in almost all cases when comparing data sets from every 5 minutes from the start to 30 min and every 5 minutes from 40 to 75 min in the vertical component. In the horizontal component, significant differences were seen for every 5 minutes between 0 to 5 min and 10 to 45, 25 to 35 min and 45 to 55 min, and 45 to 55 min and 65 to 70 min. Significant differences were frequently obtained for subject B between the vertical standard deviation every 5 minutes from 5 to 45 min and those from 45 to 85 min, except for the period from 65 to 70 min. In addition, significant differences were seen for every 5 minutes only between 20 to 25 min and 65 to 70 min in the horizontal component. The vertical standard deviation of both subjects A and B tended to increase towards the middle stage and decrease towards the end of the task, but this common tendency was not seen in the horizontal deviation. The vertical components of these two subjects showed the same tendency and even showed similar significant differences in the early stages, the middle stage, and the end stage of the task. Subjects E and G (Figs. 4 (c) and (d)) also showed significant differences in their vertical and horizontal standard deviations. The other subjects (D, F, I, J) also showed tendencies in their significant differences that were similar to those of subjects A and B. That is, significant differences were obtained in almost all cases when comparing data obtained every 5 minutes in eight subjects.

4. Conclusion

To confirm that changes in the standard deviation of eye movement at gaze points during a task is an effective basis for measuring fatigue, we had subjects perform simple calculation problems for 90 min. By extracting the gaze points during the task, we were able to compare the horizontal and vertical standard deviations of eye movements every 5 min on average and the number of answers. Two of our subjects, A and B, showed a common trend in their vertical standard deviations of eye movements, number of answers and decrease in CFF. Additionally, subjects E and G showed a correlation in their horizontal standard deviations of eye movements and number of answers. CFF was used as an indicator of the degree of fatigue. The number of answers every 5 minutes correlates with the standard deviation of eye movements. Therefore, number of answers of subjects with a correlation may suggest the internal state of the subject, such as his or her degree of concentration and degree of fatigue. Significant differences were also seen in the other four subjects not discussed here when comparing standard deviation every 5 minutes during the task. It was suggest that certain internal changes in subjects can be evaluated by analyzing standard deviations at gaze points during work. However, it was in only four of eight subjects that significant differences were found for the number of answers and an increase or decrease in the standard deviation of eye movement. A change in the number of answers may not necessarily reflect some kind of internal changes in the subject. Therefore, comparison with other physical parameters such as brain waves, near infrared spectroscopy (NIRS), and galvanic skin response (GSR) will be necessary to clarify what brought on the changes in standard deviation of eye movements. Differences in the quality of gazing, that is, differences between seeing (non-careful gaze) and watching or looking (careful gaze), can be an important factor in gaze analysis when the subject is driving a car or evaluating image quality. Hence, we expect that the study presented here will be applicable not only to fatigue evaluation but also to future studies on gaze quality.

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