

The Act of Task Difficulty and Eye-movement Frequency for the 'Oculo-motor indices'

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Abstract

The oculo-motor reflects the viewer's ability to process visual information. This paper examines whether the oculo-motor was affected by two factors: firstly task difficulty and secondly eye-movement frequency. In this paper, oculo-motor indices were defined as measurements of pupil size, blink and eye-movement. For the purpose of this study, two experiments were designed based on previous subsequential ocular tasks where subjects were required to solve a series of mathematical problems and to orally report their calculations.

The results of this experiment found that pupil size and blink rate increased in response to task difficulty in the oral calculation group. In contrast however both the saccade occurrence rate and saccade length were found to decrease with the increased difficulty of the task. The results suggest that oculo-motor indices respond to task difficulty. Secondly, eye-movement frequencies were elicited by the switching frequency of a visual target. Pupil size and the saccade time were found to increase with the frequency however, blink and gazing time were found to decrease in response to the frequency. There was a negative correlation between blinking and gazing time. Additionally, the correlation between blinking and saccade time appeared in the higher frequencies.

These results indicate the oculo-motor indices are affected by both task difficulty and eye-movement frequency. Furthermore, eye-movement frequency appears to play a different role than that of task difficulty.

CR Categories: H.1.2 [User/Machine Systems]: Human information processing [H.5.2]: User Interfaces Evaluation/methodology

Keywords: Eye-movement, Pupil Size, Blink, Saccade, Gaze

1 Introduction

The oculo-motor systems are driven by a viewer's mental activity such as problem solving. It has been found that eye pupil

and blink respond to psychological and cognitive difficulties [Beatty 1982] [Tada et al. 1991]. It has also been noted that pupil size increases in accordance to increased task difficulty [Beatty 1982] and emotions [Hess and Polt 1964]. Therefore this information can be used as an index to estimate an individual's Mental Workload (MWL) [ISO 1991] for a task [Osuga 1992].

Eye-movement is also known to change in accordance to the level of mental activity an individual is engaging in [Takeda 1976]. The change of saccade and gaze happens in response to the change of blink or pupil size [Takahashi et al. 2000b], however what still remains unclear is the role and possible relationship between eye-movement and task difficulty. An issue of particular importance was the attempt to establish which particular components of eye-movement were significantly affected by a change in task difficulty. In this paper, some measures were compared in order to extract possible relationships, these evaluations were then used to construct oculo-motor indices that acted as measurements for pupil size, blink, saccade and gaze. The oculo-motor indices changed differently among the viewing tasks of our previous experiments: simple subsequential ocular task with an oral response task, a driving simulation task which was conducted with a video-game computer [Takahashi et al. 2000a] [Takahashi et al. 2000c] [Takahashi et al. 2000b]. It was hypothesized that a viewer's mental workload would increase in response to the oral response task and that a similar phenomena would occur in the driving-simulation condition. However, it was assumed that the responses of saccade, blink and gaze would be different amongst the various tasks. Some factors were considered as reasons for the possible differences between the two experimental conditions: for example subject's attention, monotony, viewing field size, etc. There was also a possibility that the frequency of eye-movement could be a contributing factor in the observed differences.

The aim of this paper was to examine whether both task difficulty and eye-movement frequency affect oculo-motor indices and the relationship among them. The following issues were addressed:

1. To examine the changes in eye-movement in response to an increase in a viewer's mental activity during a subsequential ocular task.
2. To examine the relationship among blink, saccade — gaze in response to the frequency of eye-movement with oral questions.

For these purposes, two experiments were devised and conducted based upon subsequential ocular task with oral questions.

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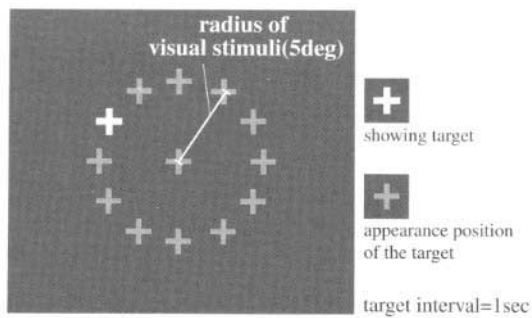


Figure 1: The subsequential ocular task

2 Experiment I

This experiment was conducted in order to examine whether eye-movement changed in response to task difficulty during a subsequential ocular task.

2.1 Experimental procedure

2.1.1 Stimuli

Subsequential eye-movement were induced in order to simulate natural viewing through the use of a visual stimuli. Subjects were asked to follow a target symbol (+) which switched periodically in each second on the screen. The sample of the stimuli is illustrated in Figure 1. The symbol switched randomly on a circle whose radius was 5 deg in visual angle. Every visual angle between the two sequential target positions was fixed to the radius at 5 deg. The visual angle of gazing was suggested at around 3 deg[Inui 1996], therefore it was assumed that every stimuli switch would motivate saccadic eye-movement. This visual stimuli was displayed on a 37 inch video monitor. A pair of speakers were placed on both sides of the monitor for providing audio instruction. The audio instructions were pre-recorded to a Mini disc, and then played back to the viewer at the same sound level.

2.1.2 Oral calculation task

The calculation tasks were given to subjects in order to activate mental activity during the subsequential ocular task. The audio instruction for an oral calculation was provided as a stimuli. The task consisted of one or two digits multiplication. For example, 23×6 , 8×6 , etc. Subjects were required to solve the multiplication problem and to give an oral answer of calculation process[Takahashi et al. 2000b].

2.1.3 Oculo-motors

The eye-movement of the left eye was observed by an eye-tracker (NAC:EMR-7), which was synchronized with pupil observation. The eye-tracker output came in the form of x-y coordinates in $\pm 0.1\text{deg}$ spatial resolution which signify the degree of eye tracking during the task. The sampling rate was 30Hz and the sessions were recorded on NTSC video.

The eye-movement speed was evaluated as differential angles per NTSC frame. To extract the saccade, the eye-movement was divided into saccade and gaze by the speed 40deg/sec [Ebisawa and Sugiura 1998]. In addition, the saccade length was computed by the summation of differential x-y coordinates of a saccade[Takahashi et al. 2000b].

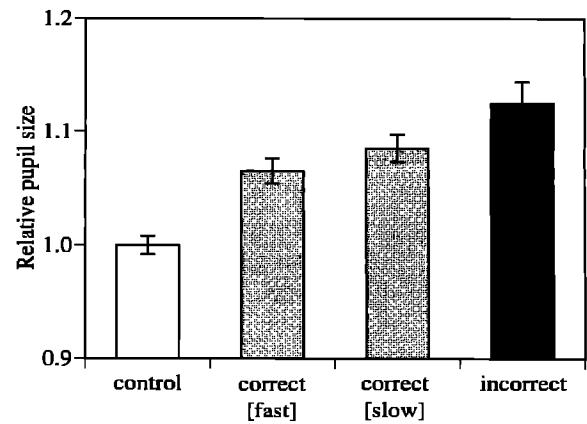


Figure 2: Pupillary change with the task difficulty

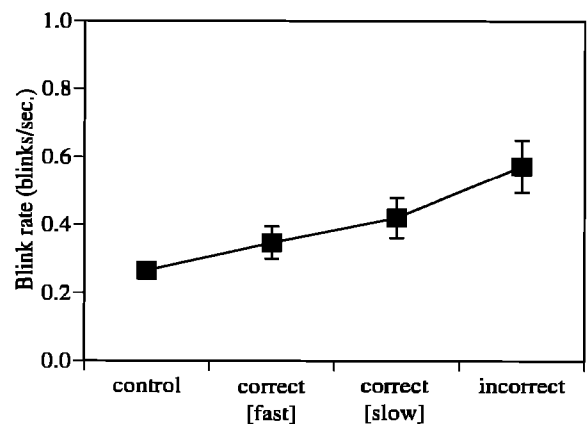


Figure 3: Blink rate change with the task difficulty

Pupil size was measured by processing the image of the eye supplied by the tracker. Blinking was detected and defined as those period where the pupil appeared to be smaller. As blinking prevented eye-movement from being detected, the data for eye-movement during the blink were not included. Both pupil and blink were also observed at 30Hz.

2.1.4 Design

Seven male university students took part in this experiment as subjects and were paid for their time. Subjects were required to respond to ten tasks, each within 10sec intervals. The following stimuli session was also conducted without any instruction as a control session.

2.2 Results

2.2.1 Definition of task difficulty

Subjects responses were divided into four conditions: control without calculation task (control), correct quick response (fast correct), correct slow response (slow correct) and incorrect response (incorrect). The average percentage correct was 80.8%, and correct responses were divided into two groups based upon subjects reaction times. Task difficulty seemed to increase response times and this

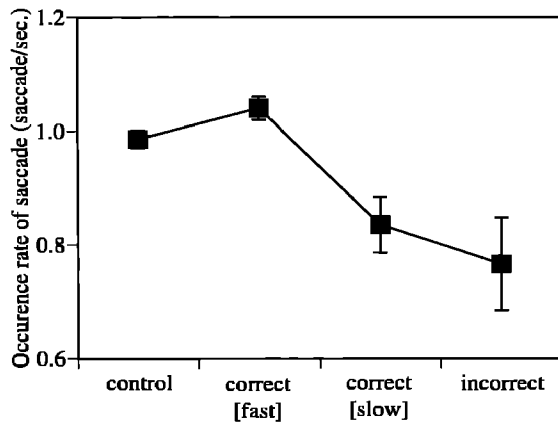


Figure 4: Saccade occurrence rate with the task difficulty

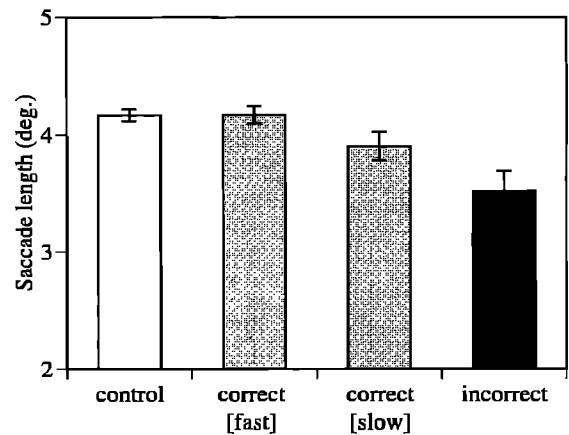


Figure 5: Saccade length with the task difficulty

was found to be the same for all four conditions. Most subjects also supported this order as the task difficulty.

Pupil size was compared among the four response conditions. Figure 2 shows average pupil size with standard error across four conditions. Pupil size was found to increase from control to incorrect response. An analysis of variance (ANOVA) was performed on the data in order to ascertain if pupil size could be affected by task difficulty. The source of response conditions was significant ($F(3,295)=18.5, p < 0.01$) when performing a one-way ANOVA. The pupil size for the response session was significantly larger than for the control session ($p < 0.01$). As with previous studies this result suggests that pupil size reflects task difficulty [Beatty 1982].

Average blink rate with standard error was also summarized in Figure 3. The figure shows that the blink rate increases in accordance to response conditions. The source of the condition found to be significant for the blink rate when performing a one-way ANOVA ($F(3,363)=9.4, p < 0.01$). The blink rates for correct[slow] and incorrect responses were significantly higher than those for the control session ($p < 0.05$). In particular, the blink rate for incorrect responses were twice those found for the control session. This finding suggests that subjects blinked more frequently when issuing incorrect responses. Both the results of Figure 2 and Figure 3 concur with subject's impression and previous studies [Beatty 1982] [Tada et al. 1991]. These findings suggest that task difficulty can be defined by both pupil and blink changes.

2.2.2 The saccade occurrence rate

To examine the influence of blink to the saccade, the saccade frequency for the response conditions were compared, because of the noted negative correlation between the blink rate and the saccade rate as suggested in a previous study [Takahashi et al. 2000b].

The occurrence rate of saccade was defined as the number of saccades per second. The change in the occurrence rate of saccade with standard error was illustrated in Figure 4. The rate for the control session was around 1.0 saccade/sec when responding to the stimuli switching interval. The rate for the correct[fast] was the same as that for the control session, however the rate decreased in the response condition of correct[slow] and incorrect. The source of the response condition was found to be significant when analysing the results using a one-way ANOVA ($F(3,241)=10.5, p < 0.01$). The rate for incorrect response was significantly lower than the control and fast correct response ($p < 0.05$).

2.2.3 The saccade length

In order to compensate for the reduced saccade frequency, the length of saccade had to be controlled. The average length of the saccade was then compared across the response conditions. The average length of saccade with standard error was summarized across the conditions in Figure 5. The figure shows that the length was shortened within the response conditions. To examine the change of length, an ANOVA was conducted. The source of the response condition was also significant ($F(3,242)=6.0, p < 0.01$). The results suggest that the length for an incorrect response was significantly shorter than for the control and fast correct response.

2.3 Discussion

Total gazing time, another measure of eye-movement, was found to significantly decrease across the response conditions. Conducting ANOVA, the source of the condition was significant ($F(3, 248) = 12.3, p < 0.01$). The relative time for gazing was compared across the conditions and results revealed that the average time for both slow correct and incorrect response was significantly lower than that for the control.

There was no significant difference for all indices between the control condition and fast correct response without pupil size. Despite gazing time significantly decreasing in the group of incorrect responses, for the incorrect response the saccade occurrence rate was the lowest and more significantly the saccade length was the shortest. This suggests that eye-movement measures are influenced by the increase of invisible time when blink rates are higher. As a result, eye-movement suppression appears in response to mental task difficulty. Furthermore, it is very interesting that task difficulty affects eye-movement behavior despite subjects having enough time in slow subsequent ocular tasks. This finding provides further evidence that task difficulty influences measures of eye-movement.

3 Experiment II

This experiment was conducted in order to examine whether the relationship among oculo-motor indices would be significantly affected by eye-movement frequency.

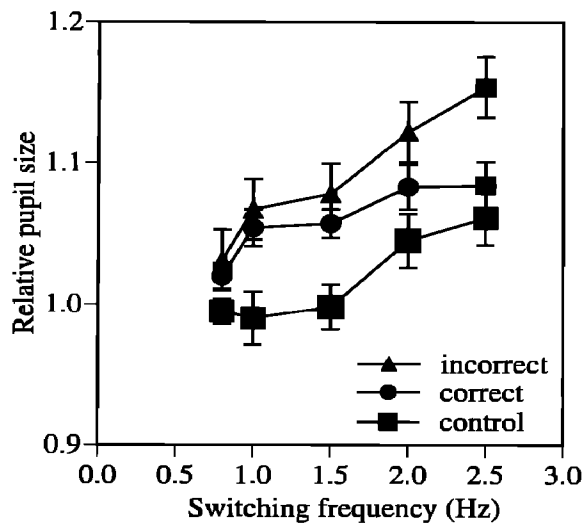


Figure 6: Relative pupil size with the target switching frequency

3.1 Experimental procedure

The same subsequential task in Experiment I was conducted. Eye-movement frequency was controlled in all levels by switching the frequency of the target symbol. An oral response task was also administered to subjects and was the same as that noted in Experiment I.

Four male university students aged between 22 and 25 years of age took part in this experiment as subjects and were paid for their time. Switching frequencies of the target were controlled at 0.8, 1.0, 1.5, 2.0 and 2.5 Hz. The switching target could evoke eye-movement in the same frequency. The control session was also conducted without any audio instruction. Therefore, the target switching frequency was added to the experimental parameters as laid out in Experiment I.

3.2 Results

In Experiment II, the responses were divided into three conditions: control, correct, and incorrect response. Because there was little difference between fast correct and slow correct in Experiment I. The percentage correct for the oral task was 83%. The eye-movements were frequent in response to the target switching, blink, saccade and gaze were evaluated as costing time rate [Takahashi et al. 2000b] in Experiment II.

3.2.1 Pupil response

Pupil size was compared among the three response conditions along with the target switching frequency. Figure 6 shows the change of the average pupil size with standard error. Pupil size increased with the response condition in the same order as that found in Experiment I. In addition, pupil size increased with target switching frequency. An ANOVA was conducted to assess the significance of the pupillary change, both sources of the response condition and the target switching frequency were found to be significant (the response condition: $F(2,492)=19.2, p < 0.01$; the target switching frequency: $F(4,492)=19.9, p < 0.01$), and the interaction of those sources was not however significant ($F(8,492)=0.6, p = 0.75$). This finding suggests that an increased switching frequency increases task difficulty and mental workload thereby making it harder to follow the visual target.

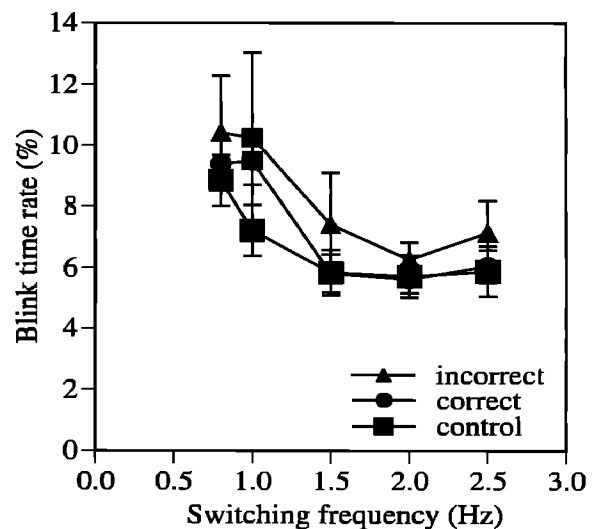


Figure 7: Blink time rate with the target switching frequency

3.2.2 Blink response

The change of blinking time rate was summarized using the same format in Figure 7. This result suggests that blink costs time for 6.11% of the total observed time. Blinking times were seen to increase across the response conditions as well as in Experiment I. However, blink decreases were noted with target switching frequency. The differences of blinks can be suppressed according to the target switching frequency. If this measure is taken then there is a small difference between the correct response and the control in higher frequency condition of target switching. Both sources of the task difficulty and target switching frequency were analysed using a two-way ANOVA and were found to be significant (response condition: $F(2,371)=5.7, p < 0.01$; switching frequency: $F(4,371)=9.3, p < 0.01$), the interaction of those sources was not significant ($F(8,371)=0.2, p = 0.98$).

In Experiment I, both pupil size and blink rate were found to increase with in line with an increase in task difficulty. Both were also seen to increase in line with task difficulty in Experiment II. Pupil size and blink do however reveal a different tendency with the target switching frequency measure. This result suggests that blink is suppressed by frequent eye-movements which are caused by the following of a visual target.

3.2.3 Gazing time

As blink time decreases, gazing time should change in accordance to its relationship to blink time. The gazing time, which was defined as the rate of gazing for the total observation period, are illustrated in Figure 8. The gazing time rate decreased across the response conditions as well as in Experiment I.

A deviation of gazing time for the control session was found to be more frequent than that for incorrect responses. The deviation decreased for higher frequencies of target switching. Both sources of task difficulty and the target switching frequency were found to be significant during an ANOVA analysis (response condition: $F(2,394)=3.0, p < 0.05$; switching frequency: $F(4,394)=4.2, p < 0.01$). The interaction of the factors was not significant ($F(8,394)=0.3, p = 0.96$). The result of this ANOVA suggests that gazing time rates decrease with task difficulty and that of target switching frequency.

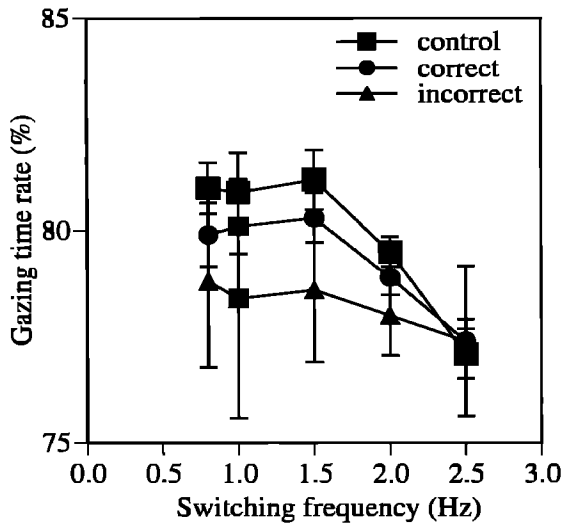


Figure 8: Gazing time rate with the target switching frequency

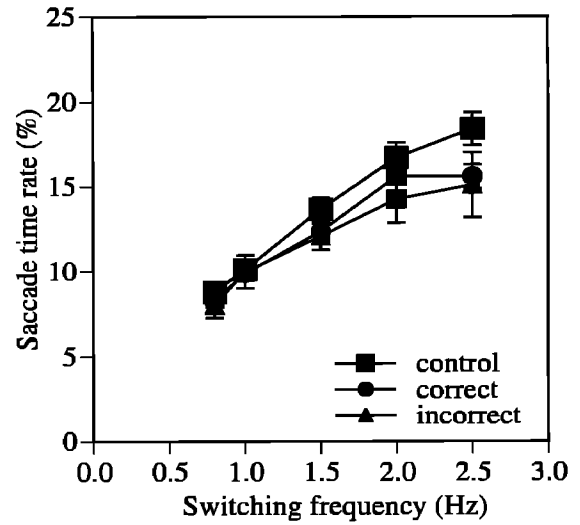


Figure 9: Saccade time rate with the target switching frequency

Table 1: Correlation coefficient between blinking and gazing time

target switching frequency (Hz)	0.8	1.0	1.5	2.0	2.5
blinking time	-0.97	-0.97	-0.95	-0.90	-0.84
-gazing time	($p < 0.01$)	($p < 0.01$)	($p < 0.01$)	($p < 0.01$)	($p < 0.01$)

Table 2: Correlation coefficient between blinking and saccade time

target switching frequency (Hz)	0.8	1.0	1.5	2.0	2.5
blinking time	-0.04	-0.21	-0.23	-0.37	-0.43
-saccade time	($p = 0.75$)	($p < 0.10$)	($p < 0.05$)	($p < 0.01$)	($p < 0.01$)

3.2.4 Correlation of blinking and gazing time

A trade-off relationship is suggested between blinking and gazing time in problem solving situations [Takahashi et al. 2000b]. The possibility of relationships within this study's data set were also examined. Correlation coefficients are summarized in Table 1.

All correlation coefficients were found to be significant and showed a strong negative correlation. The trade-off relationship was examined within those coefficients. It was found that blinking time rates increased within the response condition, despite gazing time rates decreasing within the condition. Both these changes consisted of negative correlations.

Additionally, the absolute value of the coefficient slightly decreased with the target switching frequency (-0.97 to -0.84). The variance of both time rates were suppressed according to the switching frequency. It was considered that the decrease of variance affects to change for the absolute value of the coefficient.

3.2.5 Saccade time

The target switching frequency must affect the saccade directly. To examine the effect of the frequency to the saccade, the saccade time rates with standard error are summarized in Figure 9. Figure shows that the saccade time rate monotonically increases with frequency. The deviation of the saccade time among the response conditions also increases with the frequency. Two-way ANOVA was conducted on the saccade time rate. Both sources of the task difficulty and the target switching frequency were found significant (response condition: $F(2,520)=5.8$, $p < 0.01$; switching frequency: $F(4,520)=42.8$, $p < 0.01$). The interaction of both sources was not significant ($F(8,520)=0.8$, $p = 0.58$). The result suggests that both task difficulty and switching frequency affect saccade time significantly, and similarly task difficulty reduces the saccade time to

follow the target.

3.2.6 Correlation of blinking and gazing time

A viewer has to have some invisible time during both blinking and saccade time. The trade-off relationship has been suggested between both blinking and saccade time [Takahashi et al. 2000b]. The correlation coefficients are summarized in the same format as in Table 2.

Results show that the correlation coefficient between blink time rate and saccade time rate gradually changed according to the target switching frequencies ($r = -0.04$ to -0.43). There was little correlation in the area of lower frequencies of eye-movement, but a significant correlation appears in frequent eye-movements over 1.5–2.0 Hz. This suggests that the trade-off relationship is dependent on eye-movement frequency. Because the eye needs to keep visible time despite invisible time increasing such as the periods when the frequency of eye-movement is higher, then a trade-off relationship appears between blink and saccade occurrence.

3.3 Discussion

Experiment II examines whether the factor of eye-movement frequency affects the oculo-motors. The target switching frequency may evoke the eye-movement frequency. Increasing the frequency of a visual target to follow may lead to a viewer's mental workload to be increased.

3.3.1 The frequency factor

Pupil size increases within the response conditions as task difficulty increases. This increase is also seen to occur when the target

switching frequency condition is applied. Both increases indicate that the viewer's mental workload increase and that this increased workload is an important factor in experimental situations. Blinking time also increases with the task difficulty of an oral calculation. This response was found to occur in Experiment I. However, blinking time decreases with the target switching frequency. The responses show different and opposite consequences between these two factors of difficulty and of frequency. This result suggests that task difficulty and eye-movement frequency are different factors of change of oculo-motor indices.

The decrease of gazing time with task difficulty as noted in Experiment I was a finding in line with a previous study [Takahashi et al. 2000b]. Gazing time was also seen to decrease with target switching frequency. Therefore, both task difficulty and eye-movement frequency can be said to affect the decrease found in gazing time. The saccade decreases with task difficulty and was noted in the findings of Experiment I and a previous study [Takahashi et al. 2000b]. According to the target switching frequency, saccade time increases monotonically. As a result, both factors of task difficulty and eye-movement frequency affect oculo-motor indices. Additionally, a change of the indices for task difficulty is independent on eye-movement frequency.

3.3.2 'Trade-off' relationship

The correlation coefficient in Table 1 indicates a strong negative correlation between blink and gazing time. The absolute value of the correlation coefficient changes in a smaller range with the frequency. This trade-off relationship has also been shown in the previous studies [Takahashi et al. 2000a] [Takahashi et al. 2000b]. However, the responses of blink and gaze were different among those. In this experiment, both task difficulty and eye-movement frequency were found to affect blink and gaze respectively. Therefore, it is interesting to consider which factor mainly affects the negative correlation. According to Figure 7 and 8, both deviation of the change are suppressed in response to the target switching frequency. That suppression may affect the slight decrease of the coefficient with the frequency.

The factor of another trade-off relationship between blink and saccade time still remains unclear, as this relation appears to depend on the particulars of the experimental condition. Table 2 shows a change in the correlation coefficient between blink and saccade time. For lower frequencies of eye-movement, the correlation coefficient is not significant. This suggests that task difficulty bears little influence to this relationship, as task difficulty is independent of the frequency. However, the relationship appears to be stronger when eye-movement frequency is higher. Therefore, the trade-off relationship between the blink and saccade time depends on higher eye-movement frequency.

4 Conclusions

This study was constructed to critically examine evaluate the oculo-motor and the role of eye-movement changes, task difficulty and mental workload. Two experiments based on subsequential ocular tasks with oral calculation were conducted.

Firstly, both pupil size and blink rates were found to increase with task difficulty. Additionally both the saccade occurrence rate and the saccade length decreased in response to task difficulty. These results suggest that oculo-motor indices change according to task difficulty.

Secondly, eye-movement frequency appears to affect the oculo-motors. It was found that the responses to the frequency are different for task difficulty, and that eye-movement frequency plays a role as another factor for oculo-motor indices. The trade-off relation

between the blink and saccade time depends on eye-movement frequency.

The results provide evidence that the oculo-motors can be a useful index for task difficulty and that eye-movement frequency affects the measures of the oculo-motor. To inspect how both factors of task difficulty and eye-movement operate in natural viewing conditions and to extract other factors of oculo-motor change are issues that require further research attention.

5 Acknowledgement

This research was partially supported by the Japanese Ministry of Education, Sports, Culture, Science and Technology (MEXT), Grant-in-Aid for Encouragement of Young Scientists, 0380, 1998–2000 and Grand-in-Aid for Scientific research, (B)(2)–10558020, 1998–2000, (C)(2)–13680228, 2001–2002.

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