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Analysis of Fatigue Difference between Paper and Displays—Measurements of Near Point Distance

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Abstract. *Emissive screens are generally believed to be the main reason for eye fatigue when reading text on displays. This study examines the impact on eye fatigue of the reading style and medium: reflective or emissive. We test three media: paper, LCD (liquid crystal display with backlight), and electronic paper (book reader using electrophoretic reflective display). Eye fatigue levels in a reading task are evaluated under two reading styles (free condition and fixed condition) for the three media by measuring the increment in near point distances after each reading task. Subjects were requested to read a novel for 180 min using the three media. The fixed reading condition yielded a statistically significant increase of the near point distance on the three media, while the free condition showed no such increment, regardless of the medium.* © *2012 Society for Imaging Science and Technology.*
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INTRODUCTION

Emerging progress in electronic display technologies has already produced high performance television displays with large and flat screens. Display technologies seem to have already successfully received customer satisfaction as television screens. On the other hand, customers are often complaining about displays as document screens. We still generally prefer reading on paper than on electronic displays[1–3]. Eye fatigue is one of general disadvantages of reading on displays. Eye fatigue is an essential subject to be solved for electronic displays[1].

Electronic paper is a promising reflective medium by which we access documents probably with more readability and less fatigue than with conventional electronic displays[4,5]. However, the main factors determining readability and eye fatigue have yet to be clarified[6,7]. The emissive screen is often simply believed to be the main reason for the eye fatigue experienced when reading texts on displays. We have not found, however, any paper which shows definitive data that an emissive screen is more fatiguing than reflective media. We need to investigate what, in fact, is the essential reason why we often feel eye fatigue when we read documents on conventional displays.

Here we should consider not only the impact of media style, reflective/emissive, but also the impact of reading style. Paper and displays offer a significant difference in reading style since computer screens are usually stationary on the desk while paper documents are usually hand held. We have already found a tendency that the hand-held reading style, regardless of reading medium, offer readers a favorable impression in terms of readability and fatigue[8]. In this study, we focused on how the reading style influences eye fatigue quantitatively.

However, quantitative evaluation of eye fatigue is not very easy. Subjective evaluations based on assessments by test readers have been generally used for evaluations of eye fatigue. Subjective assessments are, however, inadequate for really quantitative evaluation because quantification of human feeling is generally difficult and unreliable. An appropriate index of physical eye fatigue is needed.

Recently, we have been studying the near point distance (NPD) [9,10] as a reliable index of eye fatigue. The NPD is the shortest distance at which a subject can focus on the target. The NPD naturally depends on the individuals. It also depends on age; it generally extends in proportion to one's age. The NPD generally increases, fortunately or unfortunately, as our eyes become fatigued. Thus, we can expect that the increase of the NPD can be utilized as a quantitative index of eye fatigue. We have already studied the relation between the increase of the NPD and a subjective assessment of eye fatigue by subjects after 270 min of reading a novel. The increase of the NPD has shown strong correlation with subjective assessment of eye fatigue[11,12].

In this article, we compare the level of fatigue when reading three media: paper book, reflective display (electrophoretic display), and emissive display (LCD). Two conditions of medium handling, fixed on the desk and free holding by a subject, were tested in each medium. We measured the increment of NPD after a reading task as a quantitative index of eye fatigue. We have focused on clarifying an essential factor of eye fatigue brought by rather long reading task.

EXPERIMENTAL METHODS

We evaluated eye fatigue in the following method and procedure. Subjects were requested to read a novel for 180 min each medium: paper book, electronic paper (electronic book reader with electrophoretic display), and display (liquid crystal display with backlight). Details of the three media

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Table I. Experimental conditions.

	Paper	Electronic paper	Display
Medium	Paper book	Electrophoretic display (LIBRIe: SONY)	LCD with backlight (mimo UM-710: Nanovision)
Screen	Area: 105 × 150 mm Contrast: 7:1. (A6 size) Mat surface	Area: 90 × 120 mm (Diagonal l: 6 inch) Contrast: 9:1. Mat surface	Area:95 × 153 mm (Diagonal: 7 inch) Brightness: 300 cd/m^2 Contrast: 400:1. Brightness: 300 cd/m^2 Glossy surface
Character × line number	38 × 14	30 × 16	42 × 16
Font size	9 pt		
Illumination	600 lx on the desk 22 Watt daylight fluorescent lamp (6700 K); 7 bulbs were equally spaced in the ceiling		
Subjects	6 students	8 students	6 students

and experimental conditions are shown in Table I. Subjects were students in their twenties whose corrected vision was over 0.6. Eye fatigue levels in the reading task were evaluated under two reading conditions for the three media. One was the fixed condition, and the other was the free condition. The increase of the near point distance (NPD) after the reading task was used, in this study, as an index of eye fatigue. Figure 1 shows a tool for measuring the near point distance. The NPD was measured using a decrement procedure, in which a focusing target moves toward the eyes of a subject; subjects were requested to stop the target just when it falls out of focus. The measuring tool has, in fact, another NPD measuring mode: the increment procedure. In the increment procedure, the focusing target moves away from the eyes of a subject; subjects are requested to stop the target when it first comes into focus. We used the decrement procedure in this study. This is because we have already found, in our former study[11,12], that the decrement procedure offers more stable results and consequently better correlation with subjective assessment of fatigue than the increment procedure.

An instrument for measuring the near point distance (accommodometer) was used in these experiments. Each medium used in this study allowed the hand-held reading style; a hand-held liquid crystal display was used in the reading task. The display parameters, i.e. display area, font size, and numbers of characters, were made almost equal for the three media.

In the fixed condition, the medium was fixed to the desk top by a support stand (the angle was set at 60° from the desk top). A constant medium angle was used for the purpose of simplifying the experimental procedure. The height of the subjects in the chair was not taken into account in our experiments. It should be considered again as a secondary factor when seriously considering the angle of the medium surface to the viewer's eye. Page turning during the reading task on the LCD was performed by pushing the buttons of a keyboard connected to the LCD. Paging action on the electronic paper was performed via the paging key on its top surface. In the free condition, any reading style including

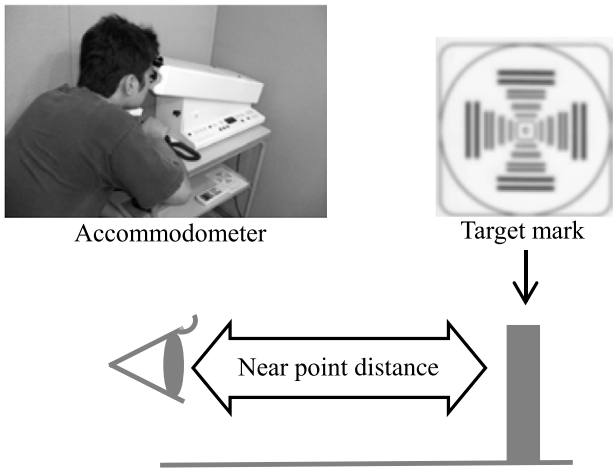

Figure 1. A tool for measuring the near point distance (accommodometer) and an illustration of its cross section.

hand holding and lying flat on the desktop was allowed, other than using the supporting stand. Typical scenes of tasks are shown in Table II. We did not dare to control the reading distance from a medium to the eyes. We considered that natural reading behavior would not be assured if the reading distance was rigidly controlled.

Figure 2 shows a time chart for measurements. 90 min reading periods were broken by a short rest of 10 min. The near point distance was measured every 30 min while reading. The near point distances were measured as the nearest distance at which the subject could focus while moving the target toward the subject. Measurements were repeated 10 times each measurement, and average values were obtained by ignoring the maximum and the minimum value of the ten measured values. This removal of the two extreme values was carried out for the purpose of eliminating possible faults by subjects in indicating the correct position of their near point. The standard deviation of the adopted eight values, after eliminating the maximum and minimum

Table II. Typical scenes of tasks.

Paper	Electronic paper	Display	
Free condition			
Fixed condition			
Medium			

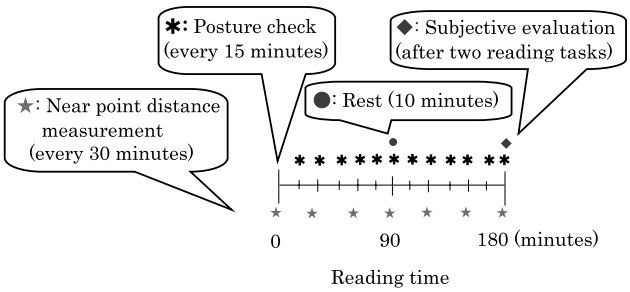

Figure 2. Time chart.

value from all the ten values, was around 5% of the mean value. Strictly speaking, the total time of reading test is a little bit longer than 190 min (including 10 min break) because each set of NPD measurements, at every 30 min, takes a few minutes. Possible recovering or fatiguing during each NPD measurement was not taken in account; we assume its effect is negligible.

The posture of the subject was checked every 15 min during the reading task; an examiner periodically observed the subjects from a one-way mirror window of the test chamber and recorded their posture on a recording sheet. The subjects were requested to provide relative evaluations between the two reading conditions (fixed and free) after completing the two reading tasks, each on the different day, for each medium. They were asked to provide information on four items: eye fatigue, eye performance, physical and mental fatigue, and sleepiness. Table III is a list of the four questions. The two questions asking about physical/mental fatigue and sleepiness are, in fact, dummy questions. We dared to ask these sacrificial questions as outlets for complaints which were not related to eye fatigue. The relative superiority of the reading condition was indicated by the subjects assigning one of five subjective assessments. Figure 3 shows a scale of relative evaluations between the fixed and free conditions.

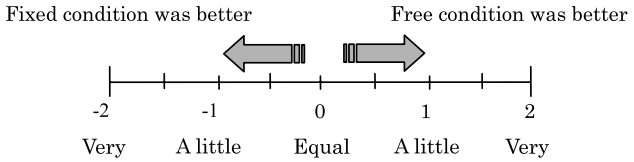

Figure 3. Scale of relative evaluations between fixed and free conditions.

The subjects were requested to experience the six reading tasks under six different conditions, namely the fixed and free reading conditions using the three different media, on six different days. This was to avoid possible accumulation of fatigue in each subject. A different order of the six reading conditions was used for each subject in order to cancel a possible order effect of reading conditions.

EXPERIMENTAL RESULTS

Near Point Distance

The rate of increase in the near point distance (NPD) was calculated every 30 min by using the following formula for each subject.

$$\text{Increase rate of NPD (\%)} = \frac{(\text{NPD before reading} - \text{NPD after reading})}{(\text{NPD before reading})} \times 100(\%).$$

Average values, for all subjects, of the increase rate of near point distance were calculated; they are plotted in Figure 4. The NPD increased only for the fixed condition, regardless of the medium.

Subjective Evaluation

Eye fatigue and eye performance are metrics of fatigue that are expected to relate to the near point distance. Figure 5 shows average results of the subjective evaluations, for all subjects, for eye fatigue and eye performance. The results of

Table III. Questions answered by subjects.

Questions	Typical complaint	Notes
(1) Eye fatigue	Dry eye, eye pain	Essential questions related to the eyes
(2) Eye performance	Bleary or blurred vision	
(3) Physical/mental fatigue	Tired, exhausted	Dummy questions as outlets for complaints not related to eye fatigue
(4) Sleepiness	Sleepy, faint	

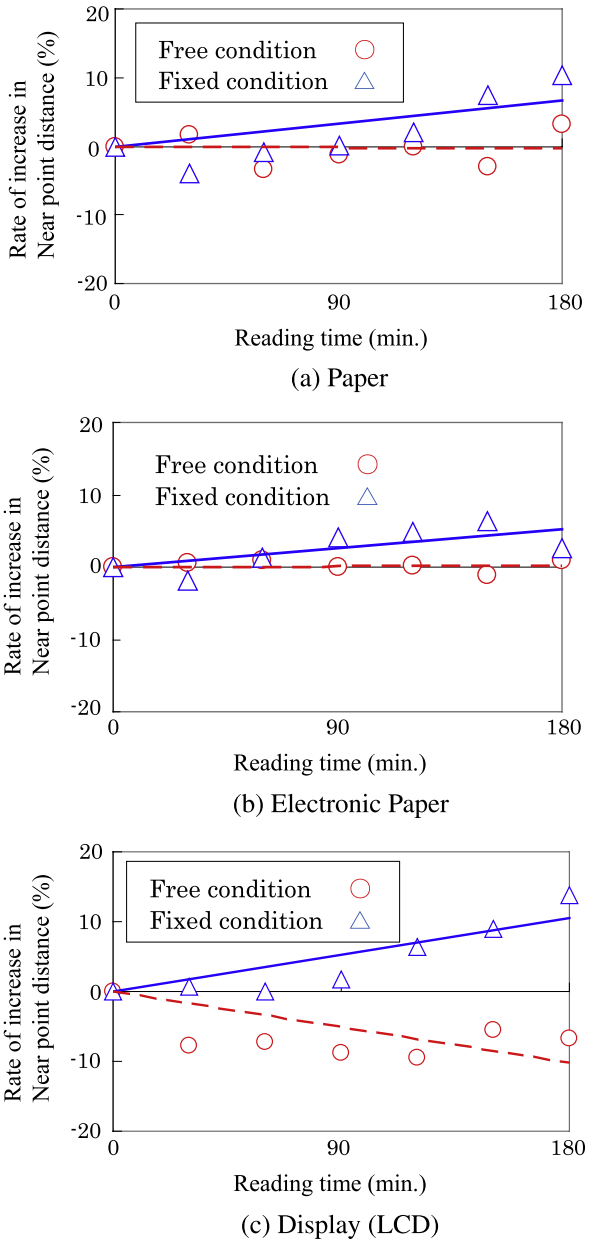

Figure 4. Rate of increase of the near point distance.

both relative eye fatigue and eye performance showed larger values than zero for all three media. This means that the free condition was superior to the fixed condition regarding the eye performance and the eye fatigue for all three media.

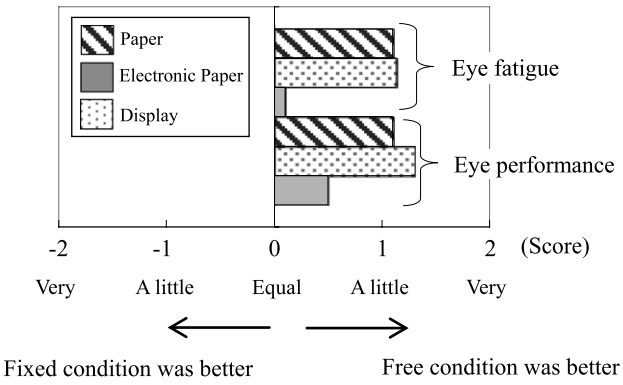

Figure 5. Subjective evaluation of the three media (eye fatigue and eye performance).

Table IV. Measured rates of medium position change.

	Free condition	Fixed condition
Paper	42% (4.7 times)	(0 %) 0 time
Electronic paper	35% (3.9 times)	
Display(LCD)	29% (3.2 times)	

Check of Medium Position

We evaluated the frequency of the subject's posture change during the 180 min reading period. We recorded the posture of each subjects every 15 min. If the subject did not have the same posture as that which was recorded the previous time, a position change was recorded. There were 12 posture check timings; so 11 times is the maximum number of posture changes. We categorized the posture of the subjects (medium position and handling style) into the following 8 categories: (1) flat on desk, (2) leaning against desk edge, (3) holding in both hands on desk, (4) holding in one hand on desk, (5) holding in both hands on the knee, (6) holding with one hand on the knee, (7) holding in both hands in the air, (8) holding in one hand in the air. We then counted the frequency of posture changes when the categories of the observed postures were different between two consecutive timings. Table IV shows the average values, for all subjects, of the posture change rates for the three media and the two conditions. For example, in the electronic paper case, the average subject changed posture 3.9 times over the 11 chances, or approximately 35% of the sampling timing. The posture change rates were naturally 0% for the fixed

Table V. Increase rates of NPD and calculated values of level of significance.

			Increase rate of NPD (%/hour)			Difference (Level of significance)
			Free condition	Fixed condition	Average	
Increase Rate of NPD (%/hour)	Reflective media	Paper	−1.00	3.13	1.06	−0.16(0.94)
		Electronic paper	0.05	1.75	0.90	
		Average of reflective media	−0.40	2.34	0.97	−0.92 (0.64)
		LCD	−3.39	3.48	0.04	
	Average of all media		−1.45	2.79		
Difference (Level of significance)			4.23 (0.02)			

condition. The posture change rate exceeded 30% in the free condition for all three media.

DISCUSSION

Correspondence in the Experiment Results

It should be noted that the near point distance increased, which indicates fatigue, only in the fixed condition regardless of the medium. This result corresponds to the subjective assessments for eye fatigue and eye performance. The frequent change in posture indicated in Table IV for the free condition suggests that the posture change might be the key factor preventing eye fatigue.

Statistical Confirmation

We performed a test to confirm if the differences in the slopes of the near point distance curves were statistically significant for the fixed and free conditions, or for the reflective and emissive media. We used Student's t test to evaluate the statistical significance of the difference between the mean values of two independent groups. Student's t test generally outputs a probability p that confirms the null hypothesis that denies the difference in the mean values of two groups. A statistical significance is confirmed when $p < 0.05$: that is, the null hypothesis should be denied. We calculated the slopes of the near point distance curves by collinear approximation of the plots for each subject; the starting points of the curves were fixed to the value before any reading task. We calculated the average values for all subjects and then calculated the p values for the two pairs: fixed and free, and reflective and emissive media.

Table V shows the values calculated for the statistical evaluation. The probability $p = 0.64$ ($P > 0.05$) for reflective and emissive media, and $p = 0.02$ ($P < 0.05$) for fixed and free. A statistical significance was confirmed only for the difference between fixed and free in our experiments. These results suggest that the inability to move the computer screen is one of main causes of the fatigue that is common when performing tasks on a computer screen. That is, electronic media that can be hand held are expected to reduce eye fatigue. Note that we are not finally concluding that the differences between reflective or emissive screens never affect eye fatigue. That is, it should be noted that our experiments were performed using a moderate lighting environment for each condition. Emissive displays may be too bright and thus fatiguing in a dark condition. Emissive displays may also be too dark under sunlight and thus fatiguing. We used moderate lighting conditions[9], 600 lx on the desk, where emissive displays must be not too bright or too dark for readers and where reflective displays are generally readable with enough level of contrast. Future work will examine the impact of lighting condition on the reading performance offered by reflective and emissive media. A lighting condition with sunlight is a typical condition to be examined.

CONCLUSIONS

Evaluations of eye fatigue were performed on three media (paper, emissive LCD, and reflective electronic paper) under two reading styles: free condition and fixed condition; the increase in the near point distance after each reading task was taken as the main metric of eye fatigue. The main results are summarized as follows.

(1) The free condition for media handling offers lower fatigue (statistically significant) than the fixed condition, regardless of the medium.
(2) The media (reflective/emissive) showed no significant difference in terms of eye fatigue.
(3) Electronic media that can be hand held are expected to reduce eye fatigue.

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