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Reading performance and visual fatigue when using electronic paper displays in long-duration reading tasks under various lighting conditions

Po-Chun Chang [a,*], Shuo-Yan Chou [a], Kong-King Shieh [b]

[a] Department of Industrial Management, National Taiwan University of Science and Technology, 43, Sec. 4, Keelung Rd., Taipei, Taiwan, ROC
[b] Department of Industrial Management, Oriental Institute of Technology, #58, Sec. 2, Sihchuan Rd., Banciao City, Taipei County, Taiwan, ROC

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ABSTRACT

In this study, the effects of ambient illuminance and light source on participants' reading performance and visual fatigue during a long reading task were investigated using three electronic paper displays. Reading on electronic paper displays was also compared with reading on paper. In Experiment 1, 100 participants performed a reading task where the display area for the text was equated for the displays. The results indicated that participants' visual performance and visual fatigue did not differ significantly among different electronic paper displays, ambient illuminance conditions, or light sources. In Experiment 2, another 60 participants performed the same reading task where the full screen of each electronic paper display was used to present the text. The results showed that reading speed differed significantly across different electronic paper displays and ambient illuminance levels. The reading speed was slower for displays with smaller screens and increased as the ambient illuminance increased. Changes in the critical flicker fusion frequency significantly differed across ambient illuminance levels. Implications of the results for the use of electronic paper displays are discussed.

1. Introduction

The electronic paper display is now the most popular of the new types of visual displays, owing to the enormous success of Amazon Kindle, which uses a reflective-type display that differs markedly from the conventional transmissive-type liquid–crystal display (LCD). Unlike a transmissive-type LCD, which uses a backlight as its pixel light source, a reflective-type display reflects ambient light as does ordinary paper and can display text and images indefinitely without additional power. The available commercial electronic paper devices include Amazon Kindle, Sony PRS-700, and iRex Reader. Although these electronic paper displays have been in the market for a number of years, ergonomics studies of such devices are limited. Isono et al. [1] conducted an experiment in which 13 college students read with an electronic paper display and with conventional paper for 90 min. The results showed no significant differences in the level of visual fatigue between electronic reading and conventional reading. Jeng et al. [2] reported that the legibility of text on electronic paper displays depends on the illuminance intensity but not on the light source, and that conventional paper had a higher visual comfort rating than electronic paper although both supported similar performance in a letter-search task.

Many factors influence visual performance and visual fatigue when using displays, e.g., the display medium, light source, ambient illuminance, polarity, and target-to-background luminance contrast. Ambient illuminance is an important factor in video display terminal (VDT) design. Many recommendations exist regarding the level of ambient illuminance. For cathode ray tube (CRT) workstations, an ambient lighting of 200–500 lx is generally suggested. The choice of illuminance level greatly depends on the task [3]. Ostberg [4] reported that a lower ambient illuminance might be more appropriate for CRT work. Xu and Zhu [5] studied the effect of ambient illuminance and found that performance deteriorated as ambient illuminance increased.

Regarding the effect of illuminance on visual performance and fatigue when using an electronic paper display, Lin et al. [6] found that illuminance had no significant effect on accuracy of visual tasks on electronic paper. Lee et al. [7] found that ambient illuminance had no significant effect on accuracy performance but had a significant effect on search speed. Shieh and Lee [8] found that different illuminances (200, 700, and 2000 lx) resulted in significantly different preferred viewing distances and screen angles. Higher illuminances (700 and 2000 lx) resulted in longer preferred viewing distances and smaller screen angles. They suggested that reflective-type displays may require higher illuminance (700 lx or higher). Wang et al. [9] and Wang et al. [10] pointed out that participants' visual performance with electronic paper displays was significantly different under various ambient illuminances. In

* Corresponding author. Tel.: +886 988177582; fax: +886 3 318 5522.
E-mail addresses: d9301301@mail.ntust.edu.tw, wolf.jamie@msa.hinet.net (P.-C. Chang).

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general, the abovementioned studies have found that the required ambient illuminance for electronic displays is higher than that for CRT or LCD displays and that the proper range may be about 500–1000 lx. The above suggestion was based on short-duration experiments using simple word identification tasks. However, an electronic paper display is typically used for reading text, and the reading time can last for hours. Furthermore, visual fatigue occurs mostly after long periods of reading. Thus, a short-duration word identification task may be inappropriate for evaluating the visual performance and visual fatigue when using an electronic paper display. Moreover, these studies evaluated an old-type Kolin electronic (Ch–LC) display and Sony e-book, which were not mainstream in the market. Consequently, there is a need to explore the visual performance and visual fatigue experienced when using popular electronic paper displays (e.g., Sony Reader, Amazon Kindle, and iRex Reader) in a long-duration reading task and how they compare with those when performing the same task on ordinary paper.

In recent years, a number of studies on electronic paper displays [2,8,7] have reported that the effect of the light source is limited; for example, a sunlight lamp (D65) was similar to a fluorescent lamp (TL84) but better than a tungsten lamp (F). However, these studies also focused on word identification tasks. Whether the results are similar for a long-duration reading task is unclear.

Many studies have compared reading on displays with reading on paper [11,12]. Slower reading speed, lower accuracy, greater fatigue, and less subjective preference were found when reading on displays [13,14]. Regarding the effect of the display medium on higher cognitive ability such as text comprehension, some studies [11] concluded that comprehension was not different for material presented on paper or displays. However, Cushman [15] found that reading speed and comprehension have an inverse relationship; for example, slower readers show better comprehension. Thus, although the display medium appears to have little effect on comprehension of reading material, it may affect reading speed and indirectly influence comprehension. However, most of the above studies focused on CRT or LCD displays and did not compare paper and electronic displays. Consequently, there is a need to explore the effects of electronic paper display media, ambient illuminance, and light source on reading performance and visual fatigue during long periods of reading.

In summary, electronic paper displays may replace conventional paper, books, and magazines in the future. Studies on electronic paper displays are very limited, and existing studies have used visual search or identification tasks and employed search speed or accuracy as dependent measures. Studies that measure higher cognitive performance and visual fatigue in long-duration reading tasks are required. In this study, we investigated the effects of ambient illuminance (200, 500, and 1000 lx, with 1500 lx added in Experiment 2) and light source (TL84 and D65) on participants' reading comprehension and visual fatigue using three electronic paper displays (Amazon Kindle DX, Sony Reader PRS-505-SC, and iRex 1000S). A comparison was also made between reading on electronic paper displays and on ordinary paper.

2. Experiment 1

2.1. Method

Two experiments were conducted in this study. The first employed the display medium, light source, and ambient illuminance as independent variables.

2.1.1. Participants

One hundred college students (53 male and 47 female) between 19 and 28 years old (mean age, 23.3 year; SD, 1.8 year) participated in the experiment. All had no prior reading experience on electronic paper displays, and had corrected visual acuity higher than 0.8 and normal color vision as tested by a Topcon screenscope SS-3 and standard isochromatic charts. There was an institutional review board (IRB) approved by the Oriental Institute of Technology, and all the participants gave written informed consent. Each participant was paid NT$300 (about 10 USD).

2.1.2. Experiment design

The first experiment evaluated three independent variables: the display medium, illuminance level, and light source with the text area controlled. Three electronic paper displays and conventional office paper were used as test visual display units. The two light sources used were D65 (6500 K) and TL 84 (4000 K). The illuminance was set at three different levels: 200, 500, and 1000 lx. Therefore, there were 18 experimental conditions [3(displays) $\times$ 2(lightsources) $\times$ 3(illuminances)]. This experiment used a between-subject design for all independent variables, and five participants were randomly assigned to each condition. Thus, ninety participants were used for conducting the tests on electronic paper displays. In addition, a comparison group (10 participants) was used for conducting the tests on A4 paper with D65 as the light source and an ambient illuminance of 500 lx. The total number of participants in Experiment 1 was 100.

2.1.3. Apparatus

The following three electronic paper displays were used: Sony PRS-700 with a 6-in. display, 800 $\times$ 600 resolution; Amazon Kindle DX with a 9.7-in. display, 1200 $\times$ 824 resolution; and iRex 1000S with a 10.2-in. display, 1024 $\times$ 1280 resolution. All use E-Ink® electronic paper technology. Table 1 lists the specifications of the three electronic paper displays. To avoid brand effects, the three displays were designated as devices A, B, and C. Fig. 1 shows the three electronic paper displays with text display areas equated. The light source and ambient illuminance were controlled using a color assessment cabinet (VeriVide CAC 120-5). The ambient illuminance was measured using a TOPCON Illuminance Meter IM-2D. According to the specification of the color assessment cabinet, the uniformity of the illuminance level was better than 5% and the screen reflection was controlled. The critical flicker fusion frequency (CFF) of a participant was measured with a Lafayette Flick Fusion Control 12023.

2.1.4. Experimental conditions

The experimental task configuration is shown in Fig. 2. The VDTs were placed inside the color assessment cabinet located on a table 73 cm in height. The front edge of the table was 17 cm from the screen center. The inclination angle of the screen was 105° with respect to the horizontal axis. The viewing distance was controlled to 50 cm by using a chin fixture. These task setup parameters were fixed during the experiment. The participants could adjust their seating height to make themselves as comfortable as possible.

Table 1
Specification of the three electronic paper displays.

	Device A	Device B	Device C
Manufacturer information	Sony PRS 700	Amazon Kindle DX	iRex 1000S
Diagonal screen size	6 in.	9.7 in.	10.2 in.
Grey scales	8	16	16
Resolution	800 * 600	1200 $\times$ 824	1024 * 1280
Display technology	E-Ink	E-Ink	E-Ink