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Minimum ambient illumination requirement for legible electronic-paper display

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ABSTRACT

The intent of this study is to determine the minimum ambient illumination requirement for legible electronic-paper display. Not only the young but also the elderly were included as research subjects. Through the method of character-search task, the results indicated that the significant performance improvement of all subjects occurred at 52 lux on the search time and at 62 lux on the subjective visual fatigue. Therefore, the minimum ambient illumination requirement for legible electronic-paper display can be synthesized at 62 lux. This minimum point of ambient illumination for the young and the elderly represents that the reflective-type display started presenting its better legibility and the subjective visual fatigue started decreasing. As electronic-paper display technology applications gradually expand, product designers need notice this fundamental limit of electronic-paper display when they continue to create possible applications in the future.

1. Introduction

Over the last few decades, many advances have been made in the area of display technology, and this dramatic change made the visual display terminals (VDT) much lighter and thinner. In recent years, the research and development of electronic-paper display technology has attracted considerable attention due to light weight, low power consumption, and sunlight readability. These advantages have revealed the vision of paper-like displays, and continuing improvements in this display technology have gradually led to new applications in many areas. In the commercial market, the well-known products are e-books based on electrophoretic technology (e.g. Sony LIBRI'e [1] and Amazon's Kindle [2]). Because of these paper-like and energy-saving advantages, this kind of display technology brings the designers more creative possibility to achieve diverse applications. For example, Motorola applied this display technology to the mobile phone products [3], and Lexar used it as a segmented-bar display for a USB memory-stick device [4]. Seiko announced the demonstration of the world's first watch to utilize an electronic-paper display [5]. Other amazing applications, such like electronic pricing labels in retail shops [6] and the displays embedded in smart cards [7], exhibited its high potential of development possibility. In the near future, applications based on electronic-paper display technology will gradually expand, with great convenience and benefit. However, in order to attain this goal, it is important to let the designers get more information about its fundamental limitation or capability.

The biggest difference between the electronic-paper display and the traditional VDT (e.g. cathode-ray tube (CRT), liquid–crystal display (LCD)) is the lighting source. The electronic-paper display totally depends on the ambient light as its reading source, in comparison with the conventional CRTs and transmissive-type LCDs which self-emit or transmit light. Hence, traditional VDT whose screen emits light does not require ambient illumination in order to be read. One can easily obtain information from the traditional VDT screen even in the complete dark condition. On the contrary, we cannot see anything from the reflective-type electronic-paper display until there is lighting in the surroundings. Since the electronic-paper display is different from other traditional displays, the ambient illumination is a critical issue when applying this display technology to product design. A key issue then is the minimum ambient illumination requirement at which human eyes find acceptable legibility from the electronic-paper display without excess visual fatigue. This fundamental information is necessary for designers when they expand this technology in other application areas in the future.

In general, in the indoor environment, the illumination condition is in the range of 50–100 lux for a dim location, in the range of 320–500 lux for a bright place, and in the range of 1000–3000 lux near the window. The ambient illumination in the range of 7000–1.3×10^5 lux is found in the outside environment, with the variability as a function of weather conditions [8]. In the last several decades, there has been a tremendous wave of interest in the relationship between ambient illumination and

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Table 1
Research summary of illumination effects on e-paper display.

Evaluation range (lux)	Findings from the previous studies of visual performance	Ref.
200, 500	Although there is no significant difference on subjects' visual performance, subjects preferred a higher illumination (500 lux)	[18]
300, 700, 1500	The e-paper display needs 700 lux or higher illumination	[19,20]
200, 800, 1500, 2200	Illumination is not a significant factor	[22]
200, 400, 800, 1500, 3000	The legibility of e-paper display increased with the illumination level in the range of 200–1500 lux and decreased at a higher illumination level	[21]
200, 1500, 3000	Ambient illumination had no significant impact	[23,24]
200, 1500, 8000	When the illumination was raised from 200 lux to 1500 lux, subjects performed better. However, when the illumination rose to 8000 lux, the subjects' search speed slowed down	[25]

visual performance on types of work. Boyce [9] pointed out that lighting itself cannot produce work output. What lighting can do is to make details easier to see and colors easier to discriminate without producing discomfort or distraction. Workers can then use this increased ease of seeing to increase output. Sanders and McCormick [10] indicated that the greater the contribution of vision to the performance of a task, the greater will be the effect of lighting on that task. Hence, lighting would be expected to have a greater effect on a reading task. The previous studies which focused on illumination effect can be classified into two major categories. Some previous studies focused on general work performance [11–13]. For most general visual tasks, the higher the level of ambient illumination, the easier it is to see [10]. Continuous increase of illumination level results in smaller and smaller improvements in performance until performance attains its best level. The point where this leveling off occurs is different for different tasks. Generally, the more difficult the task, the higher the illumination level at which this occurs [13].

Other previous studies investigated the VDT task performance [14,15]. Most of them were based on CRT or LCD mediums. Although these traditional VDT do not need ambient illumination, the lighting is required to carry on other tasks performed in conjunction with VDT work, such like looking at the keyboard [10]. However, the ambient illumination needs to be carefully arranged using these traditional VDT screens because the higher ambient illumination reflects off the screen and makes it more difficult to see the information [10]. Reflection on the screen due to high ambient illumination reduced the contrast between the characters and background and decreased the display legibility [16]. Therefore, Sanders and McCormick [10] indicated that the recommended illumination levels for traditional VDTs are a compromise between the higher levels demanded for general works and the low levels required for reading the screen. For example, ambient lighting of 150–500 lux is generally suggested for CRT work [17]; the normal ambient illumination of 450 lux might be more appropriate for TFT-LCD work [15].

More recently, there has been a shift in attention to the reflective-type electronic-paper display. Wang et al. [18] investigated the visual performance under 200 lux and 500 lux using the simulated electronic paper, and indicated that there is no significant difference on subjects' visual performance. However, subjects preferred a higher illumination (500 lux). They explained that the difference between 200 and 500 lux appeared insufficient to cause differences in subject's visual performance, but higher illumination may improve user subjective preferences. Lee et al. [19] and Shen et al. [20] both pointed out that the legibility of electronic-paper display increased as the ambient illumination increased from 300, 700 to 1500 lux and they recommended that the electronic-paper display needs 700 lux or higher illumination. In the higher ambient illumination, Jeng et al. [21] evaluated the ambient illumination including 200 lux, 400 lux, 800 lux, 1500 lux, 3000 lux and indicated that the legibility of electronic-paper display increased with the illumination level in the range of 200–1500 lux and decreased at a higher illumination level. However, there appears to be a lack of consistency in some relevant research results. Wang et al. [22] investigated the users' comprehension under 200 lux, 800 lux, 1500 lux, and 2200 lux using electronic-paper display, and showed that the illumination is not a significant factor. Lin et al. [23,24] indicated that ambient illumination (200 lux, 1500 lux, 3000 lux) had no significant impact on the legibility of the simulated electronic paper. Their explanation for this is that they used the anti-reflection or anti-glare surface treatment in the experiment, and it may more or less eliminate discomfort for higher illumination. In the extremely high illumination, Lin et al. [25] pointed out that when the illumination setting was raised from 200 lux to 1500 lux, subjects performed better. However, when the ambient illumination setting rose to 8000 lux, the subjects' search speed slowed down. Most of the previous researches focused on the general or higher illumination levels to discover recommended level (see Table 1). We have already had the concept of recommended illumination level for electronic-paper display. However, the relationship between the low ambient illumination and legible electronic-paper display is of importance to find out the fundamental limitation of e-paper display. As related applications based on electronic-paper display technology continue to expand, this information provides the display designers with overall information for further possible application.

User's age is another critical factor in VDT research because of the phenomenon of presbyopia for people over 40 years of age [26]. Since the information-oriented society encompasses the elderly, it is important to consider the vision of aged people when developing display devices [27]. In the last several decades, there have been numerous studies in the literature dealing with age effect on VDT visual performance [27–29]. In general, the visual faculties gradually decline with age, especially for the people exceed 40 years old. Loss of elasticity of the lens deteriorates near vision and makes the elderly people become farsighted. The accommodative ability of the eye decreases with age, and this condition is known as presbyopia [30–32]. In addition, the muscles controlling the diameter of the pupil begin to atrophy with age. This reduces the size of the pupil and decreases the range and speed with which the pupil can adjust to differing levels of illumination [10]. Therefore, the retinal illumination actually decreases by 66 percent from the age of 20–60 [33]. Kubota [27] evaluated the reflective-type display under ambient illumination of 500 lux, and indicated that the older subjects preferred a much higher contrast and background lightness than the young subjects when the character size was smaller than 15 pt. Because the difference in visual function of adjusting illumination, different age people must be considered when investigating the minimum ambient illumination requirement for legible electronic-paper displays.

There have been a large number of research studies using different assessment methods for VDTs. Legibility is one important human factors criterion for VDTs. ISO 9241-3 [34] defined legibility as the visual properties of a character or symbol that determine the ease with which it can be recognized. Sanders and McCormick

[10] indicated that legibility is the attribute of alphanumeric characters that makes it possible for each one to be identifiable from others. Legibility depends on such features as stoke width, form of characters, contrast, and illumination. To assess display legibility, Boschman and Roufs [35] found that searching tasks performed on pseudo-texts is an effective means. Several research papers have employed this method to evaluate the legible VDTs [19,23,24]. On the other hand, visual fatigue is another critical criterion for assessing VDTs. This measure generally can be classified into subjective and objective measurements. With regard to subjective measurement, most researchers involved the use of subjective questionnaires or interviews to understand the subject's feeling during the experiment [36,37]. Some previous studies pointed out that employing subjective questionnaires is easy to administer and can at times be more sensitive than objective measurements [38,39]. Since the minimum ambient illumination requirement needs more sensitive method to discover, the legibility and subjective visual fatigue were considered as two important aspects for evaluating electronic-paper display in this study.

The objective of the present study tries to discover the minimum ambient illumination requirement that human eyes get acceptable legibility from the electronic-paper display.

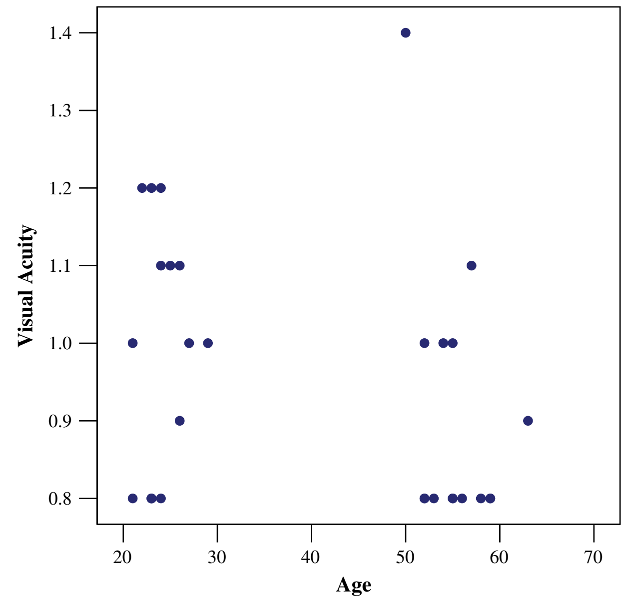

Fig. 1. Scatter plot of visual acuity as a function of age.

2. Methods

2.1. Experimental design

Since the objective of this paper is to discover the minimum ambient illumination requirement for legible electronic-paper display, the illumination setting range must begin in very low level. There were several pro-tests to evaluate the possible beginning illumination setting. The initial value of the setting needs to satisfy the condition that the subjects can complete the visual tasks. According to the pro-evaluation, 32 lux is finally decided as the beginning level in the formal experiment. Ambient illumination and user's age were two major independent variables. There were seven levels in illumination setting: 32 lux, 43 lux, 52 lux, 62 lux, 71 lux, 82 lux, and 92 lux. In addition, two age groups were investigated: 15–30 years (young adults), and 50–70 years (elderly adults). Therefore, there were seven (illumination levels) × two (age groups) experimental combinations, total 14. Each subject completes the character-search tasks in seven different ambient illumination conditions. The three dependent variables collected from the character-search tasks were search time and accuracy (for legibility) and the difference of questionnaire scores (for subjective visual fatigue).

2.2. Participants

The young and the elderly groups were separately recruited in this experiment. Each group consisted of 15 subjects. In the young group, the participants included college students and graduate students. Their mean age was 24.1 years with a standard deviation of 2.22 years. In the elderly group, the participants included retired teachers from senior high school, university staffs, and social welfare institution workers. Their mean age was 55.3 years with a standard deviation of 3.32 years. All participants were well-educated and had a lot of reading experience on electronic devices. All subjects had 0.8 corrected visual acuity or better and normal color vision. An OPTEC 2000 vision tester and Standard Pseudo Isochromatic charts were used to test the visual acuity and color vision of the subjects. The scatter plot of visual acuity as a function of age is shown in Fig. 1, and the analysis of Pearson-product moment correlation showed that there is no obvious correlation between age and visual acuity ($\gamma = -0.267$, $p > 0.05$). All participants we recruited had the similar better visual acuity.

2.3. Apparatus and experimental environment

The electronic-paper display used in this study was STAReBOOK [40] produced by eREAD Technology Company [41]. The STAReBOOK was electrophoretic electronic ink (e-ink) products, which had a resolution of 600 × 800 and 4-level grayscale. The dimension of its display was 6.4 in. black–white screen. The dimensions of the e-book were 188 mm (Length) × 118 mm (Width) × 8.5 mm (Height), and the weight was 176 g. A photograph of this electronic-paper display is shown in Fig. 2. The content shown in this display in this experiment was an image with black characters on a white background (positive polarity). A color assessment cabinet (VeriVide CAC 120-5) with a diffuse light source of TL 84 (4000 K) was used to control different levels of illumination (see Fig. 3). The ambient illumination was measured with TOPCON IM-3 photometer. In the experiment, the electronic-paper display was placed inside the color assessment cabinet with no interference from any external light source, and a bookshelf was used to support the display.

2.4. Conditions of workplace

The experimental configuration of workplace is shown in Fig. 4. The display inside the color assessment cabinet was placed on a 73 cm height table. The center of the display was 36 cm from the front edge of the table with respect to the horizontal axis, and was 10 cm high from the table. The inclination angle of the display was 105° with respect to the vertical axis [42]. A chinrest was used to restrain the subject's head 25 cm above the table and to fix the viewing distance at 50 cm during the experiment. These task set-up parameters were fixed to all subjects, who were free to change the height of the seat for their comfort.

2.5. Task design and experimental procedure

A series of character-search task was conducted to evaluate the minimum ambient illumination requirement for legible electronic-paper display. Several paragraphs of pseudo-text in Chinese were

Fig. 2. Electrophoretic e-ink display (STAReBOOK) used in the experiment.

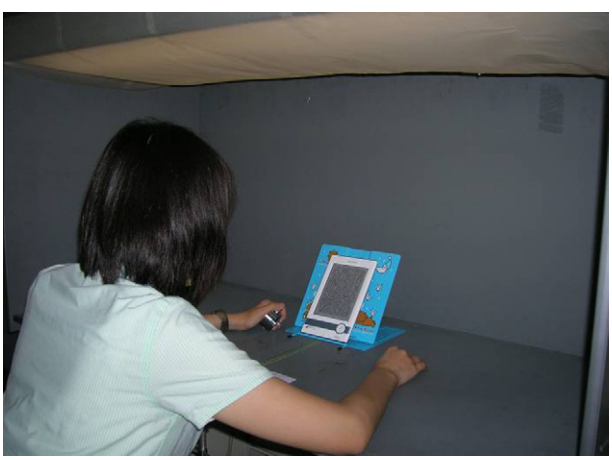

Fig. 3. A color assessment cabinet used in this experiment for producing different ambient illumination levels.

treated as the content of electronic-paper display. In each illumination level, 1600 Chinese characters [43] which were statistically reported with high frequency during 1980–1990 in Taiwan were selected for the experimental task. The pseudo-text was composed of these 1600 Chinese characters and Chinese punctuation marks (Fig. 2). These Chinese characters were 12 point font size of New Thin Ming type. Although the constitution of the pseudo-text in Chinese in each illumination level was the same, the sequence of these 1600 Chinese characters was randomized. Hence, the appearance was different in each illumination level.

There were three target characters in each experimental combination. To avoid influence of target character complexity, one target character was high level complexity (more than 13 strokes, e.g.

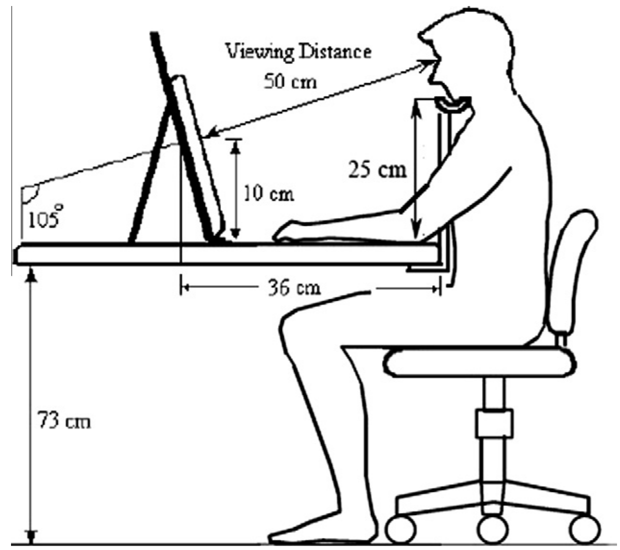

Fig. 4. The arrangement of workplace used in the experiment.

繁), another was medium level complexity (between 8 and 13 strokes, e.g. 教), and the other was low level complexity (less than eight strokes, e.g. 安) which was based on the study of Shieh et al. [44]. Subjects needed to identify one specific target character at a time, and therefore they scanned three times back and forth in total. The procedure was designed to simulate 5129 characters of reading text in each experimental combination. The target characters were randomly embedded in the pseudo-text, and the number of each target character was 19–25. However, total numbers of target character in each experimental combination were the same.

Two age groups including the young and the elderly were instructed to complete the character-search tasks. During the experiment, they were requested to identify the target Chinese characters as accurately and quickly as possible. In order to reduce the mental workload, a Baqi HK-102A counter was used by subjects to record the number of targets. Therefore, the subjects pressed the counter once while they identified one target letter instead of memorizing the total counts during the experiment. Each subject completed several training trials in order to become familiar with the whole process before the formal experiment. After each experimental combination, the subject took a rest to avoid excess visual fatigue. Each subject was instructed to complete the character-search tasks in seven different ambient illumination conditions. The sequence of seven conditions is randomized. Each subject was paid in this experiment. As an incentive to encourage active participation, in each age group, the participant who is in the top five of the highest accuracy was awarded an extra bonus.

2.6. Data collection and analysis

Two performance aspects including legibility and subjective visual fatigue were investigated. Legibility was evaluated by the search time and the accuracy of search task. The search time was the total task completion time of the experiment. Accuracy was calculated as the ratio of the number of target characters detected by the subject to the actual number of target. On the other hand, subjective visual fatigue was determined by a questionnaire developed by Heuer et al. [45]. The questionnaire was comprised the following six items:

(1) I have difficulties in seeing.
(2) I have a strange feeling around the eyes.
(3) My eyes feel tired.

Table 2
The mean values of search time under each ambient illumination level and Tukey HSD post hoc test results.

Independent variable (lux)	n	Search time (s)	Tukey HSD post hoc test grouping[a]		
Ambient illumination					
32	30	894.00	A		
43	30	830.03	A	B	
52	30	768.13		B	C
62	30	746.73		B	C
71	30	741.13		B	C
82	30	698.10			C
92	30	683.90			C

[a] Values with the same letter are not significantly different. The significant level among A, B, and C is at $\alpha = 0.05$.

(4) I feel numb.
(5) I have a headache.
(6) I feel dizzy looking at the display.

The subject answered the items on a 10-point scale, with one representing "not at all" and 10 representing "yes, very much." The sum of the responses to these items was taken as a raw score. At the beginning of each experimental condition, the subject was asked to fill out this questionnaire which elicited information concerning his/her feeling of visual fatigue. This value was treated as a reference value while the subject was in the rest condition. After completing an experimental task, the subject filled out this questionnaire again, and subjective visual fatigue was evaluated as the difference between these two raw scores of questionnaire.

In this study, three dependent measures collected from the character-search tasks were search time, accuracy and the difference of questionnaire scores. Although the underlying scale level of subjective visual fatigue is ordinal, the results within non-parametrical and parametrical analysis were similar. Therefore, three dependent measures were analyzed by the multivariate analysis of variance (MANOVA), and the Tukey HSD post hoc test was then used for multiple comparisons. The MANOVA method considered the inter-correlation of the dependent variables. All statistical analyses were calculated using the Statistical Products and Services Solution (SPSS). The level of significance was $\alpha = 0.05$.

3. Results

The results of MANOVA indicated that ambient illumination (Willks' $\lambda = 0.669$, $p < 0.05$) and age (Willks' $\lambda = 0.475$, $p < 0.05$) had significant effects on the whole dependent measures. However, there is no significant interaction between ambient illumination and age (Willks' $\lambda = 0.957$, $p > 0.05$).

3.1. The ambient illumination effects

With regard to the individual dependent variables, ambient illumination significantly influenced the search time ($F(6, 196) = 6.972$, $p < 0.05$) and subjective visual fatigue ($F(6, 196) = 11.472$, $p < 0.05$). However, ambient illumination was not the significant factor ($F(6, 196) = 0.404$, $p > 0.05$) on the accuracy performance.

Table 2 presents the mean search time of all subjects under each ambient illumination level. With the ambient illumination of 32 lux, 43 lux, 52 lux, 62 lux, 71 lux, 82 lux, and 92 lux, the mean search times were 894.00 s, 830.03 s, 768.13 s, 746.73 s, 741.13 s, 698.10 s, and 683.90 s, respectively. In general, search time decreased as illumination increased from 32 lux to 92 lux. Ambient illumination was further analyzed by Tukey HSD post hoc test (Table 2). As can be seen in Table 2 and Fig. 5, there is a significant performance improvement when the ambient illumination increases above 52 lux. Hence, the 52 lux level represents a key point.

Table 3 presents the mean values of difference of questionnaire scores of all subjects under each ambient illumination level. While the ambient illumination levels were 32 lux, 43 lux, 52 lux, 62 lux, 71 lux, 82 lux, and 92 lux, the mean values of the subjective visual fatigue were 16.70, 12.67, 12.40, 9.50, 8.73, 7.20, and 5.67, respectively. The larger difference of questionnaire scores meant that the subject felt more visual fatigue. Hence, subjective visual fatigue decreased as illumination increased from 32 lux to 92 lux. In the same way, Tukey HSD post hoc test was used as shown in Table 3. As can be seen in Table 3 and Fig. 6, there is a significant subjective visual fatigue improvement when the ambient illumination increases above 62 lux. Hence, the ambient illumination of 62 lux was the minimum level that the subjective visual fatigue started decreasing while reading on the electronic-paper display.

3.2. The age effects

With regard to the individual dependent variables, age had significant effects on the search time ($F(1, 196) = 84.102$, $p < 0.05$), accuracy ($F(1, 196) = 34.193$, $p < 0.05$), and subjective visual fatigue ($F(1, 196) = 12.344$, $p < 0.05$). In respect of the search time measure, the mean values for the young and the elderly were 668.90 s and 863.10 s, respectively. As shown in Fig. 7, the young had higher search speed than the elderly did in each illumination level. In respect of the accuracy measure, the mean values for the young and the elderly were 0.91 and 0.86, respectively. As shown in Fig. 8, the young received higher accuracy than the elderly did on the character-search tasks. In respect of the subjective visual fatigue, the mean values of difference of questionnaire scores for the young and the elderly were 11.89 and 8.93, respectively. As shown

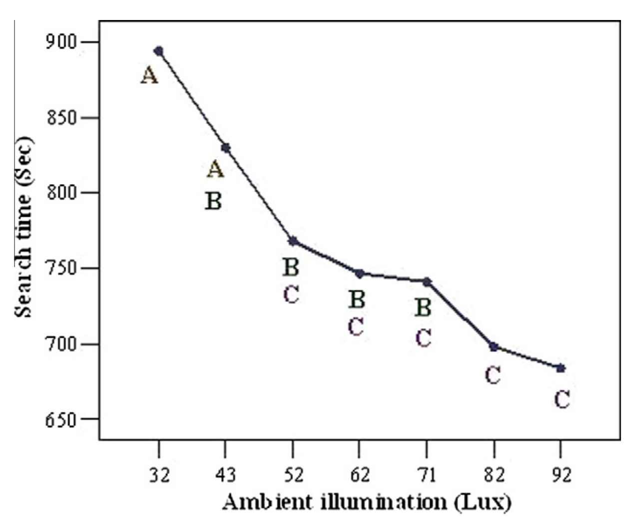

Fig. 5. The search time as a function of ambient illumination (values with the same letter are not significantly different).

Table 3
The mean values of difference of questionnaire scores under each ambient illumination level and Tukey HSD post hoc test results.

Independent variable (lux)	*n*	Difference of questionnaire scores	Tukey HSD post hoc test grouping[a]		
Ambient illumination					
32	30	16.70	A		
43	30	12.67	A	B	
52	30	12.40	A	B	
62	30	9.50		B	C
71	30	8.73		B	C
82	30	7.20			C
92	30	5.67			C

[a] Values with the same letter are not significantly different. The significant level among A, B, and C is at $\alpha = 0.05$.

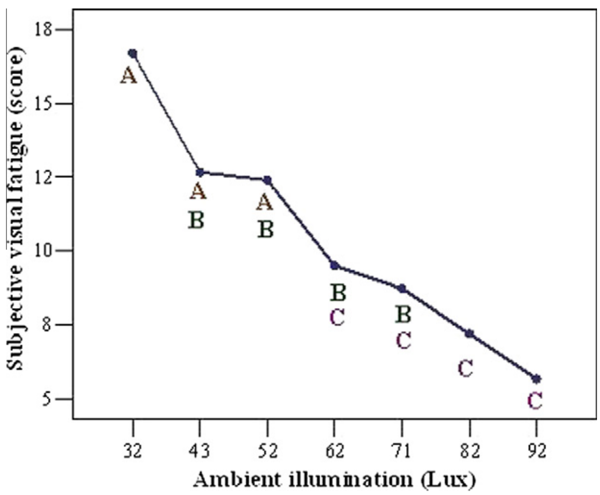

Fig. 6. The subjective visual fatigue as a function of ambient illumination (values with the same letter are not significantly different).

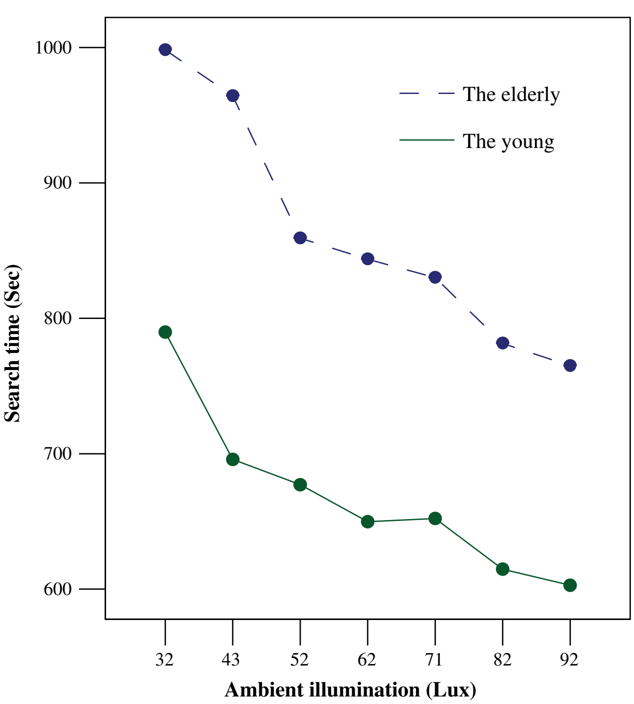

Fig. 7. The search time performance of the young and the elderly.

in Fig. 9, the young felt more visual fatigue than the elderly did in each illumination level.

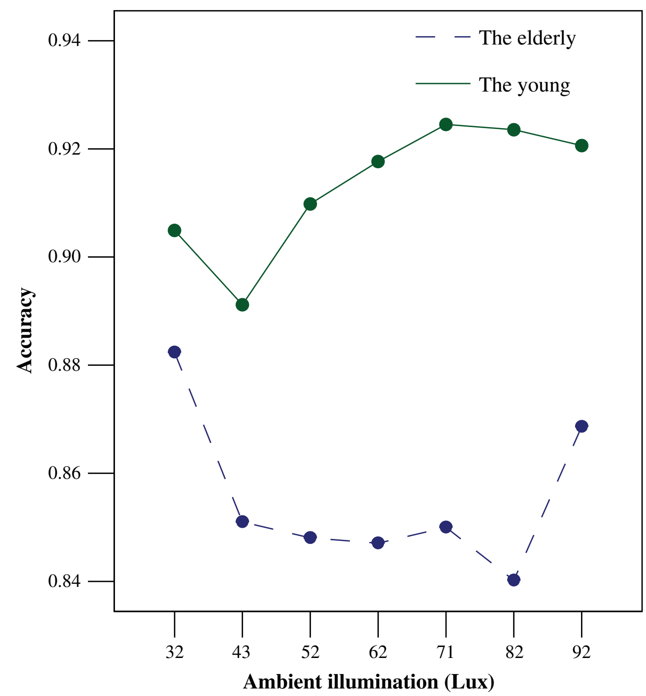

Fig. 8. The accuracy performance of the young and the elderly.

4. Discussion

In this study, we examined the minimum ambient illumination requirement for legible electronic-paper display. The present study focused on the ambient illumination factor. Because of the difference in visual function of adjusting illumination, the visual performances of the young and the elderly were analyzed together to obtain the general minimum illumination requirement.

4.1. The minimum ambient illumination requirement for legible electronic-paper display

In this study, ambient illumination showed significant effect on most dependent measures except the accuracy measure. These results appear to be in line with the findings of Boschman and Roufs [35], who found that accuracy was not a sensitive performance measure in the search tasks. In addition, it was expected that subjects would pay more attention on accuracy due to the reward policy, and they might have slowed down their search speed to attain a better performance. This may be a good reason why accuracy under each level of ambient illumination was so close and high whether for the young or elderly group (see Fig. 8). Since subjects kept their accuracy at high levels, the effects of the ambient

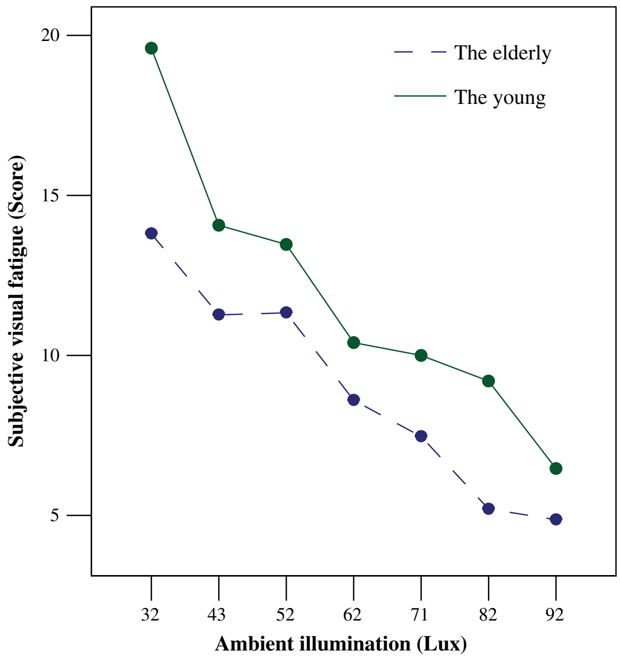

Fig. 9. The subjective visual fatigue of the young and the elderly.

illumination on legibility were highlighted only by the search time. Therefore, the minimum ambient illumination requirement for legible electronic-paper display can be determined by the search time and subjective visual fatigue.

In the present study, we examined the display legibility and users' subjective visual fatigue in low ambient illumination and validated that lighting is the key factor while using the electronic-paper display. In general, enhancing ambient lighting could continue to improve the display legibility and reduce subjective visual fatigue with the illumination range of 32–92 lux. Since the significant performance improvement of all subjects occurred at 52 lux on the search time and at 62 lux on the subjective visual fatigue, the minimum ambient illumination requirement for legible electronic-paper display can be synthesized at 62 lux. The findings of the present study indicated that 62 lux was the minimum ambient illumination level for the young and the elderly that the reflective-type display started presenting its better legibility and the subjective visual fatigue started decreasing.

Up to now, there have been several electronic-paper display researches which focused on the illumination impacts. Based on these previous results and the findings of the present study, the fundamental capability of electronic-paper display can be roughly obtained. We cannot see anything from the electronic-paper display until there is lighting in the surroundings. As the ambient illumination increases, 62 lux was the minimum ambient illumination requirement for legible electronic-paper display. When the ambient illumination level above 62 lux, enhancing ambient lighting can continue to improve the display legibility and reduce subjective visual fatigue. In the general illumination level, the legibility of electronic-paper display increases with the illumination level in the range of 200–1500 lux [19–21]. Hence, Lee et al. [19] and Shen et al. [20] both indicated that 700 lux or higher illumination was the recommended level for electronic-paper display. However, when the ambient illumination continues increasing to the extreme high level (above 1500 lux), the display legibility will be deteriorated [21,25].

It is interesting to compare ambient illumination impacts between the reflective-type electronic-paper display and the self-illuminated display. For self-illuminated displays, users can easily get the information in the dark surroundings since these screens emit light. However, enhancing the ambient illumination reflects off the screen makes someone more difficult to see the information on the screen [10]. Even so, because people do not work by self-illuminated display alone, ambient illumination is required to carry on other related works [10]. There have been a number of previous researches which provided several recommended standards. Most of these recommended lighting standards for self-illuminated display were relatively low. For example, The Illuminating Engineering Society (IES) specified 50–100 lux for general lighting where traditional VDTs were used [46]. The Human Factor Society recommended 200–500 lux [47]. For the specific display type, 150–500 lux was recommended for CRT work [17]; 450 lux might be more suitable for TFT-LCD work [15]. According to these previous studies and our findings, the relationship between the ambient illumination and display type was generally obtained. Compared to self-illuminated displays, the legibility of electronic-paper display is limited in the low ambient illumination area. The present study extended the illumination scope to low ambient illumination and discovered that ambient environment for electronic-paper display should exceed at least 62 lux. This value is the key start point and baseline for legibility.

4.2. The age effects on visual performances

Age factor significantly influenced the dependent measures including the search time, accuracy, and subjective visual fatigue. As aspect of the legibility, the results of the present study indicated that the young had higher search speed and higher accuracy than the elderly did. This is due to the difference in visual function of adjusting illumination between the young and the elderly. From the previous studies regarding the age effect on the human vision, for the elderly group, the increased opacity of the lens, coupled with the smaller pupil diameter, reduces the amount of illumination reaching the retina [10]. Weale [33] found out that there is a 50% reduction in retinal illumination at age 50, compared to age 20, and this reduction increases to 66% at age 60. Hence, even if in the same illumination level, the young got better visual performance than the elderly did. Because the vision faculties of the elderly declined, the elderly needed more time for the character-search tasks.

As aspect of the subjective visual fatigue, the results of the present study showed that the young felt more visual fatigue than the elderly did on the character-search tasks. This means that the young group was more sensible when the illumination setting changed, in comparison with the elderly group. In the same illumination condition, the young group also reported more visual fatigue than the elderly group did. This may be explained by the difference of cognitive task experience between the young and the elderly. In general, compared to the young, the elderly have the slower response and lack of sensitivity to ambient environment change. Hence, this may be the reason that subjective visual fatigue of the young was much higher.

4.3. The implication of the findings

The increased prevalence of electronic displays brings more efficiency and convenience to our dairy life. However, some problems and limits also accompany if the ambient condition is not just right. Take the self-illuminated display for example; anyone who tries to use a laptop in a bright lighting environment will know how difficult these electronic displays can be viewed. Unwanted reflection due to the bright environment deteriorates the display legibility and causes more visual fatigue. In addition, these self-illuminated displays, which constantly maintain an image with a high frequency, not only consume valuable battery life but also cause eyestrain. Fortunately, the bi-stable electronic-paper display potentially offers an efficient electricity-saving alternative that only requires power to refresh the image. Since this kind of new display technology is reflective-type, it is expected to fit to a variety of illumination levels.

Although the electronic-paper display solves the most problems of the self-illuminated display, there are some accompanying limits which are worthy to be studied. Contrary to the self-illuminated display, most important limit of all is how capacity it had in low ambient illumination. In this study, we evaluated the legibility and subjective visual fatigue and tried to detect the minimum ambient illumination requirement for electronic-paper display. To synthesize the results of two aspects, the ambient illumination of 62 lux was the minimum point of ambient illumination for the young and the elderly. Therefore, it is suggested that ambient environment for electronic-paper display should exceed at least 62 lux for different age users.

In these recent years, the market is now finally ready to embrace electronic-paper display, as indicated by its inclusion in several application products, ranging from e-books to mobile phones, indicator labels and signs [48]. Lexar applied it as a segmented-bar display for a USB memory-stick device [4]. This memory meter allows users to see how much memory is free on the device, even when it is unplugged and not powered. Graham-Rowe [48] indicated that electronic shelf-label market is a very promising way. This is the idea of replacing the traditional paper price labels on supermarket shelves with dynamic electronic-paper versions that can be updated across the store at the click of a computer button. In the near future, more applications based on electronic-paper display will continue to be created. These novel applications should base on the fundamental knowledge of the relationship between the display and human vision. The findings of the present study provided designers with capacity and limit of electronic-paper display. Furthermore, it is expected that designers expand more creative possible applications without ignoring the fundamental limits of display itself.

4.4. Limitations of the study and future research

The findings of this study provided the minimum ambient illumination requirement for legible electronic-paper display. However, the results are directly applicable only to the similar text-only stimulus under a florescent light source (TL 84). If the content includes other information formats, such like pictures or maps, the results may be different. Similarly, if the electronic-paper display is used under other light source, the results may change as well. These related issues are worthy to be investigated in the future research.

5. Conclusion

The minimum ambient illumination requirement of different age users for legible electronic-paper display has been discovered in the present study. The results revealed that 62 lux was the minimum key point that the reflective-type display started presenting its better legibility and the subjective visual fatigue started decreasing. Therefore, product designers need notice this fundamental limit of electronic-paper display when they continue to create possible applications. The ambient environment for electronic-paper display should exceed at least this basic illumination to meet the ergonomics requirements.

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