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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