H28 (2016) Doctoral Dissertation

MEASURING THE READABILITY OF ELECTRONIC DEVICES: A STUDY OF THE EFFECTS OF ILLUMINANCE, FONT SIZES, AND VISUAL ACUITY

Department of Information Engineering,
Graduate School of Information Science

First/Last name **Ranson Paul Lege**

Main Research Advisor **Professor Masato Edahiro**

December 14, 2016

Acknowledgment

I would like to express my deepest appreciation to Dr. Masaru Miyao and Dr. Satoshi Hasegawa for their generous time and support in assisting me as I struggled along to complete the necessary work for this dissertation. With the help of their lab team, I was able to conduct and write this study. This gratitude includes a nod of thanks to Dr. Takehito Kojima, Dr. Shigusa Matsunami, and Dr. Akihiro Sugiura as all three were very gracious in putting up with my many persistent questions. In addition, I would like to thank professors Masato Edahiro and Shuji Morisaki for their invaluable reading and adding many constructive comments to this research effort. Special thanks also goes to Dr. Hiromu Ishio and Dr. Nobuhiro Ishio both of who took on the role as mentors in encouraging me to finish up this work. Lastly, I have to thank my wife, Atsuko Hosono, who patiently stood by me as I labored through the many late hours to finish up this dissertation.

Abstract

At present, the commercial development of visual display terminals (VDTs) is moving at a rapid pace. The market is replete with many gadgets made for all ages. These devices require both visual and tactical manipulation and can affect a person in a variety of ways. Consumers of such products should not only be wary of price and quality but the safety of such devices. In this respect, safety refers to visual fatigue which is related to the performance of the reading device. While the International Organization for Standardization attempts to keep pace with the market changes, many of today's advances are moving ahead of the recommended standards for usage of such products. Thus, this dissertation focuses on the effects of illuminance, font size and visual acuity on the ability of people of all ages to read from such devices.

The field of ergonomics is concerned with understanding how humans interact with other systems (particularly mechanical) and as such has done much work in areas related to the impact of computer technology on the physical well-being of humans. Influences such as environmental lighting, contrast ratios, visual distance, font type and sizes as well as the condition of the individual eye are all of concern when studying the interaction between human beings and such technology. As such, this dissertation focuses on the effects of environmental illuminance, font sizes and visual acuity because they

cover an environmental factor (lighting), a mechanical element (fonts) and elements of the human condition (aging and lens cataract cloudiness).

The study encompasses a look at some of the main VDTs available on the market today including the backlit type Liquid Crystal Display (LCD), e-ink with the front light type (Electronic Paper Display with an Integrated Light Unit), and the standard E-ink or E-reader (Electronic Paper Display without front light). Much of the literature has focused on the readability of LCDs and so the primary interest in this study is a comparison of these two different types display terminals.

This dissertation represents the combination of three different experiments that studied the readability of various electronic devices under different aspects of environmental conditions and visual performance. All three experiments included the participation of 95 or more subjects in measuring and evaluating the ease or difficulty of reading in English from various devices under different conditions. The main reason for using English was because of an interest in the development of globalized standardization with regard to the usage of electronic devices. Conventional paper text was used as a comparative reference because manufacturers of such products often claim that their innovations are close to paper.

In the first experiment, 110 participants took part in a study that evaluated the performance of an LCD, an Electronic Paper Display (EPD), and an EPD with an Integrated Light Unit (ILU-EPD) under 14 different levels illuminance. The experiment included both objective and subjective measures. First, the participants read aloud from a text block for each level illuminance, and the experimental team collected the correct number of responses. This procedure was done for each device including the paper text. Second, after reading from text block of words, the readers evaluated the readability of each device using a Visual Analysis Scale (VAS). The results indicated that all the devices were equally readable between 200-500 *lx*; however, the readers rated the LCD and ILU-EPD as easier to read at less than 200 *lx* compared to paper and the EPD with no additional lighting system.

The second experiment looked at the readability of the Courier font type and sizes on different visual display terminals. Courier is a monospaced font type that allows for ease of objective measurement in terms of evaluating the visual performance of electronic devices. In this test, 99 readers grouped according to age looked at and evaluated 8, 12, and 16 point sizes on an LCD and electronic device, with paper text as a reference. A two-way ANOVA was used to check for significance. The results from this experiment found that individuals under 65 years of age could read at the 8 point size while those over 65 years of age found it difficult.

The third experiment measured the effects of aging, visual acuity, and lens cataract cloudiness on the legibility of two fonts displayed on an e-paper device. The study compared the legibility of a serif font (Times New Roman) and sans serif type (Helvetica) as discrepancy exists in the literature as to which font type is best for screen terminals. The study included 133 participants who were measured according to their binocular near visual acuity for 50 cm. The results from this experiment indicated that the legibility of e-paper displays is influenced by age, cataract cloudiness, and 50 cm visual acuity.

The results of the above three evaluation experiments reported in this dissertation provide useful knowledge on the readability of characters of various types of e-book terminals. The central aim of the study is to assist in establishing criteria for the safety of users by contributing to international standardization.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Introductory remarks

With the rapid expansion of electronic reading devices, for usage at home and work, consumers face daunting challenges to keep up with the technology but also may be unaware of the safety and health issues related to the use of such products. Meanwhile, the International Organization for Standardization (ISO) provides much of the needed specifications to ensure that products are safe, but some of the standards may lag behind the rapid advances being made in such devices as e-readers and LCDs. With respect to electronic reading devices, people of all ages can be affected by font sizes and environmental lighting in terms of visual fatigue [1].

This dissertation represents the aggregate of three separate experiments with respect to the performance of the devices under controlled environmental conditions as well as how human conditions interact with such reading terminals. The concern with the first two experiments is with readability; that is, how well individuals can read devices such as tablets and e-papers under minimum conditions of environmental illuminance and font sizes. In these two experiments readers evaluated the readability of electronic reading devices. The third experiment focuses on the effects of aging and visual acuity on the legibility of fonts on e-paper devices, which are presumed to be closer to conventional paper.

The experiments conducted for this research should contribute to the growing field of ergonomics as they involved the interactions of both environmental and human conditions on the legibility and readability of electronic devices. Thus, the aim of this dissertation is to provide the findings from the three experiments as a way to contribute to the field. The experiments used objective and subjective measurements to look at the effects of illuminance, font sizes, and visual acuity on the readability of different electronic devices. However, the purpose of this chapter is to outline the general background of the problem, explain the purpose of the experiments, sketch the methods and provide an overall map of the dissertation.

1.2 Background

Both computer technology and delivery of communications have grown exponentially over the past twenty years. Along with these developments have been increasing improvements in screen innovation, which is a key to visual performance of any such device. The markets are flooded with many “visual display terminals” (VDT) such as computers, mobile phones, reading devices, and augmented glasses. Buyers today face a multitude of choice and information regarding all of these innovations and mechanical gadgets. Many prospective buyers of VDTs are not only confused by the choices but simply cannot keep up with the rapid changes. Most consumers are unsure of the differences between such things as a Liquid Crystal Display tablet (ex. iPad) and an eReader (ex. Kindle Paperwhite).

In buying a VDT, the consumer should consider not only practical matters such as costs and quality but how well the product functions under various environmental conditions. Many of the differences in such display terminals relate directly to the performance of the screen under conditions of illuminance, viewing distance, contrast ratios, and font sizes [2] [3]. Moreover, the physical state, especially the eyes, can affect how well an individual perceives and handles the information displayed on such screens. For example, physical conditions related to aging, cataracts, and visual acuity play a role in how the individual interacts and reads such devices. Thus, the essential aim in this study concerns both environmental and human factors on the performance electronic reading devices.

The two primary screen technologies of concern in this dissertation are those found on tablet devices (such as Liquid Crystal Display) and those that are considered reflective (e-paper). Both screen technologies can trace roots that developed from a long series of discoveries that evolved from the cathode ray tube (CRT) in 1897 [4]. In 1960, the RCA laboratories produced the first transmissive optical effects that were applied to commercial items such digital watches and pocket calculators, and this in turn would lead to the Liquid Crystal Display tablet (LCD) [5]. Since the 1990s, such screens have been primarily manufactured in a range of products such as smartphones, computers and televisions.

The LCD screen uses electrical currents to adjust the backlight through filtered polarized film that becomes an image provides, which explains why they are times referred to as backlit devices. In addition, products such as the New iPad are appealing to some consumers as they are versatile, offer colored pixels, and have a faster refresh rate so that viewers can enjoy videos and gaming. One of the main criticisms targeting such tablet devices regards the visual performance of the screens in either outdoor conditions or under higher levels of illuminance indoors as glare becomes an issue. Much of the research indicates that while these tablet products are readable under dimmer light, they become harder to read in outdoor conditions [6].

Meanwhile, manufacturers have made major strides in developing eReader, E-paper or E-ink devices (such as Kindle, Havon, Fujitsu), particularly with screen performance. The technology within these devices relies on an electrophoretic process that attempts to mimic the appearance of ink on paper. Most of these devices usually produce black and white text, though at present a few products have incorporated color screens. In contrast to tablet displays, the e-paper screens have a slower refresh rate and thus are not as practical for showing videos or game applications. However, these VDTs have other advantage relative to the tablet screens. As E-ink paper screens are reflective, research indicates that they are superior in direct sunlight [7], require smaller battery power, and can be integrated with photo-voltaic power sources [8].

The manufacturers advertise that eReaders are a form of “electronic paper” claiming that these products are closer to actual paper texts, however, such claims remain in dispute. For example, Heikenfeld *et al.* has opined that for producers of these devices to justify their claim, they need to measure performance using the same metrics found in the printing industry [9]. As the technology develops, and manufacturers compete in their respective markets to improve the screens in their products, much of academia focuses on the debate over eye strain and visual fatigue which can affect legibility and readability.

Nishimura *et al.* found that Japanese adult participants in their study evaluated eReaders over LCD tablets because they appeared to reduce eyestrain under indoor conditions of illuminance [10]. Kretzschmar *et al.* challenged this view by arguing that subjective evaluations were poor indicators of readability simply because readers perceived the devices differently, and that backlit LCDs were better for the elderly [11]. Using both subjective and objective measures, Siegenthaler *et al.* found that ten subjects in their study evaluated the two display types fairly equally under indoor conditions [12]. Finally, Benedetto *et al.* stated that when less experienced readers attempt to handle VDTs, they tend to prefer conventional books over mechanical reading displays because such tactile familiarity with paper causes less visual fatigue [13].

Many variables exist with regard to reading from any type of mechanical screen or paper display. Those problems associated with reading performance can include lighting, the capabilities of a specific device as well as the health and physical condition of the reader, for example, aging, the degree of lens cloudiness, and visual acuity. The effective performance of a device can include such parameters as the contrast ratios, the glare, the color gamut, viewing angle, power requirements, switching speed and the choices of font display.

Both indoor and outdoor lighting can cause glare or reflection that hampers or interferes with the readability of screen display [14]. The advantage of conventional paper text is that lighting has less of an impact (unless it has a glossy surface) in terms of glare. The sun or any given light source can result in direct glare that shines into a person's field of vision, making tablet screens very sensitive to this phenomenon. In addition, reflection occurs when light that bounces off any particular glass, polished or shiny surface (such as on VDTs). These problems not only interfere with reading but can be a major source of discomfort, particularly for the elderly, in that can cause eyestrain and fatigue [15].

Meanwhile, there has been much debate over which font type and size provides the optimum reading enhancement for electronic devices. Bernard *et al.* conducted a comparative study of eight font types (four serif and four sans serif) at the 10, 12 and 14-point sizes and found no significant difference in reading efficiency in terms of size or type [16]. However, in this same study, participants read Times New Roman (serif) and Arial (sans serif) more quickly but perceived the Arial, Courier (serif) and Georgia (serif) as most legible. While many studies have endeavored to look at the best font sizes and types, fewer studies have sought to look at the smallest legible types or sizes that may impact both legibility and readability, especially on the elderly.

Compounding the debate, there has been the long standing schism between supporters of the serif type and those who believe sans serif enhances the readability of electronic devices. Proponents of the serif family (Times New Roman, Courier) have argued that these font types flow better [17], are better spaced and more cohesive [18] and are preferred more among users of such devices [19]. Advocates for the sans serif family (Arial, Helvetica) insist that these types of fonts are better for the following reasons: they reproduce better at smaller font sizes [20]; they are simple and uniform; and they are easier for children to read [21] or even for the seeing impaired [22] [23].

1.3 Purpose

According to the Japan Industrial Standard, readability refers to reader's capacity to discriminate, recognize and interpret a group of characters in a text [24]. As mentioned, there are many factors that affect readability including the light source, polarity, and the ambient illuminance as well as font sizes and types. A few studies have looked at the effects of ambient lighting on visual performance and font sizes, but the results have been mixed. Shieh and Lee found that reflective displays may perform better above 700 *lx* [3], while Wang *et al.* concluded that readability was different for various levels of ambient lighting [2].

The general consensus seems to be that reflective devices perform better than LCDs above 500 *lx*, but more research is needed in order to understand how well readers of all ages rate the use of e-devices in various tasks and conditions. In this vein, the research for this dissertation includes the results from three different experiments that looked at readability of devices either under different lighting or with various types of font sizes. The first experiment required readers to rate the readability of three devices under levels of illuminance. The second experiment included a study that looked at how well participants could read various font sizes from three different terminals. The third experiment sought to understand how different age groups with different levels of visual acuity would evaluate two different fonts (Helvetica and New Times Roman) from an e-paper device.

1.4 Methods

This section briefly explains the sampling and provides a general idea of the methods used in each of the three experiments highlighted in the dissertation. The methods are further detailed in the respective chapters that elaborate on each of the experiments. For each of the three studies, the participants signed a consent form to partake in the given experiments, and the Ethical Review Board in the Graduate School of Information Science at Nagoya University granted approval for the research. The formatting and style is a mixture of what the Institute of Electrical and Electronic Engineers (2005) recommends and the expectations of the Graduate School of Information Science at Nagoya University.

1.4.1 Experiment One

The aim of the first experiment was to understand to what extent people could read e-paper devices under various conditions of ambient illuminance that could occur indoors. In this study, 110 young to elderly subjects participated in an experiment to evaluate the effects of 14 different levels of ambient lighting as they read from three different electronic devices and a paper text.

The experiment included both an objective and subjective measurement. The participants were asked to undergo a timed reading task and then to evaluate the readability of two e-Reader devices (a regular electronic display and one with a front light) and compare it to a backlit Liquid Crystal Device (LCD). A conventional paper text was used as a frame of reference. The subjects employed a Visual Analytical Score (VAS) to rate the readability of the devices.

1.4.2 Experiment Two

The second experiment required different age groups to evaluate the effects of three font sizes on the readability of e-paper devices. The experiment included 99 participants asked to compare the readability of three font sizes (8, 12, 16 points) while reading from three different VDTs (Kindle Deluxe™, Apple iPad™, and paper). The objective measurements checked the reading speed and correct answer rate of the readers from the various devices that displayed the different font sizes. The readers had to count a set number of *M's* from a test block within a short duration. An ANOVA and Scheffé multiple comparison procedure was used to check for statistical error. After each reading, the subjects rated the devices with a Visual Analytical Scale (VAS) in order to match the two types of measures.

1.4.3 Experiment Three

The aim of this experiment was to collect basic data on the legibility of displayed characters on e-papers because manufacturers have claimed that these products are proficiently close to paper text. The experiment analyzed the effects of ageing, visual acuity, and cataract cloudiness on the legibility of different size characters on an e-paper device (Amazon Kindle Paperwhite). The participants in the experiment included 133 males and females between the ages of 17 and 79 years. The participants read from a string of random set of capitalized letters whose font size declined from large (18 pt) down to small (2 pt). The experimental readings employed the use of Times New Roman and Helvetica for the tasks. The participants were required to read aloud a character string, and then a systematic evaluation was used to calculate for the correct reading of each character within the two font types.

1.5 Dissertational outline

This section will describe the direction or map of this research study. This dissertation includes five chapters, tables and figures as well as the appropriate references. The first chapter provides the overall structure of the study and gives a brief background to the research, the purpose of the experiments, and a brief explanation of the methods. Chapters 2-4 will discuss each of the respective experiments in detail and provide results and discussion regarding the outcomes. Chapter 2 presents the results of the first experiment which asked participants to evaluate the readability of several VDTs under 14 different levels of illuminance. Chapter 3 discusses the results from the second experiment which compared the readability of font sizes on different electronic devices. Chapter 4 describes the results from the third experiment which sought to explain the effects of aging, visual acuity, and lens cloudiness on the legibility of two different font types on an e-paper device. The final chapter represents the conclusion and summary discussion for the dissertation.

Chapter 2: Measuring the Effects of Lighting on the Readability of Electronic Devices

2.1 Introduction

Since the 1990s, screen image quality has improved significantly, but the debate over the advantages of reading from paper text versus electronic texts continues in much of the literature [25] [26]. Despite improvements, many of the issues with the effects of lighting remain. Compared to paper, screens of all types either emit light or reflect it in such a way as to interfere with viewing. Essentially, the paper medium is less susceptible to the extremes of lighting because it is more diffuse or reflective; therefore, it serves as a reference when comparing VDTs in many different studies. Thus, the main question in this dissertational study concerns an understanding of how readers would rate the visual performance of three different display types under various levels of ambient illuminance.

In the field of ergonomics, the term ambient illuminance simply refers to the total available natural and artificial light in a room. Whether at home or office, rooms that are either dimly lit or that have light sources causing immense glare, can significantly impact a reader as well as on overall worker productivity [27]. Under such lighting conditions, a person is likely to suffer eyestrain, headaches, or reduced performance while attempting complete some reading task. As such, the lighting in a room should be sufficient enough to assist in either the legibility or readability required from a display screen.

As the many screen types and products provide different capabilities, the issue of lighting recommendations for VDTs may refer to a particular range of sufficiency. For example, in the United States, the Occupational Safety and Health Administration (OSHA) recommends a range of 200-500 *lx* when working with computers indoors [28]. Meanwhile, the International Organization for Standardization (ISO) has recommended 300-500 lx for using such technology for indoors. However, in both instances, these standards speak mainly to the effects of lighting on transmissive or tablet screens similar to LCDs as they are used more frequently for occupational purpose relative to the more leisurely reading done with e-papers with their reflective screens. As Becker states, the International Organization for Standardization is revising the standards with respect to the conditions of ambient illumination for the testing of reflective and transparent display screens [29].

The experiment discussed in this chapter endeavored to contribute to the existing knowledge base by comparing reader performance of several devices under 14 levels of ambient lighting. The study included a comparison of a LCD (New iPad), an electronic paper display (Kindle DX) and an electronic paper display with an integrated light unit (Amazon Kindle Paperwhite). In addition, these devices were in turn compared to conventional plain paper text as point of reference. The experiment included both an objective and subjective measurements. First, the study measured the reading speed of the participants undergoing the tasks, and then asked readers to evaluate each of the devices under the different levels of illuminance.

2.2 Methods

The purpose of this experiment was to have participant volunteers complete a specific reading task of short duration and evaluate the readability of several devices with respect to 14 levels of lighting. The task required the subjects to read aloud from four terminal devices placed in a cubicle under 14 different levels of ambient lighting. The participants needed approximately 40 minutes to complete the 56 separate readings from each device (one reading per every level of illuminance). During the readings, the evaluator counted the number of words read per 15 second duration while also controlling the levels of illuminance. After completing each reading for each device, the participants evaluated the terminals based on a subjective appraisal.

2.2.1 Participants

The study included 110 Japanese nationals with a near equal gender participation of 54 females to 56 males. The ages of the readers ranged from 19 to 86 years old (Mean 45.7; Standard Deviation 17.8). Participants who required the assistance of glasses or contact lenses were allowed to use them in the experiment. Prior to the experiment, readers were told that the purpose of the study was to evaluate the performance of the devices rather than a measurement of their reading abilities. This explanation was necessary in order to reduce any concerns over personal reading abilities with regard to the use of the English language.

2.2.2 Task Design and experimental conditions

As recommending by the ISO, the readings of the devices took place in a darkened room under artificial lighting conditions (Figure 1). Natural conditions of lighting can vary widely, making consistent measurements of readability difficult, which explains the rationale for establishing such an artificial condition [30]. In order to adjust to constant illumination, the setup design of the compartment included a D65 (6500k) fluorescent light and a LED light source with the same color temperature which acted as a light diffuser. The D65 is often used as a standard illuminant because it is close to the light seen on a clear day at noon. For each device, there were 14 levels of ambient illuminance that were tested (10, 20, 50,100, 150, 200, 300, 500, 750, 1000, 1500, 2000, 5000 and 8000).

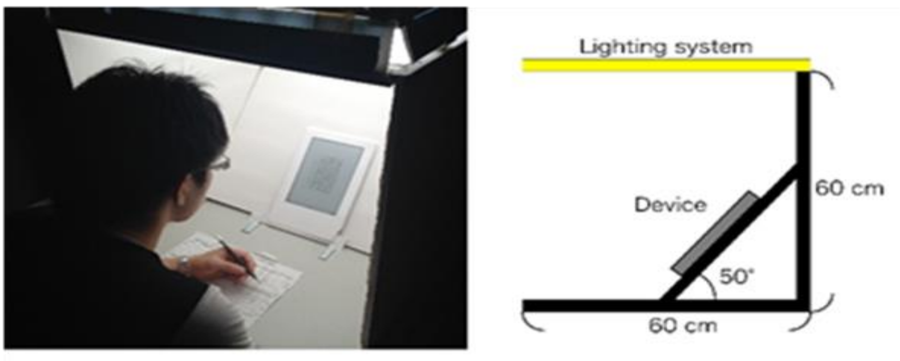

Figure 1 The equipment set up for experiment.

Participants read a text block from three different VDTs set at the maximum luminance setting, regardless of the illuminance condition. The three devices (Table 1) included an Amazon Kindle DX (EPD), an Amazon Kindle Paperwhite (ILU-EPD), and an Apple New iPad (LCD). The Kindle Paperwhite included an integrated front light to assist with glare. The specifications for these three VDTs are shown in Table 1 below. The three devices were compared to conventional plain paper (PPC), which had a whiteness of 67 percent. The contrast ratios for the VDTs were measured when each device was placed inside the compartment as it received illuminance from both the light unit above and the diffusion in the cubicle.

Table 1 Specifications for electronic device

	EPD	ILU-EPD	LCD
Manufacturer	Amazon	Amazon	Apple
Product	Kindle DX	Kindle PW	New iPad
Screen size(inch)	9.7 inches	6 inches	9.7 inches
Matrix Size	1,200 x 840	1,024 x 768	2,048 x 1,536
Resolution	1200 x 840	1024 x 768	2048×1536
Max. brightness (cd/m^2)[1)]	0	90.8	373.5
Min. brightness (cd/m^2)[1)]	0	6.2	2.9
Actual Contrast Ratio[2)]	-	14.6	128.8
Display type	E-ink	E-ink	LCD

Notes:

1) The maximum (white) and minimum (black) brightness values were measured from 1 m distance under dark room conditions.
2) The actual contrast ratios were calculated from both maximum and minimum brightness values.

The experiment included both objective and subjective measurements in order to assess the performance of the devices under different lighting [31]. The study is interested in contributing to a global standard for the ambient illuminance for e-paper devices. As English presently represents the international language, alphanumeric words were used in the reading test block. First, the subjects were allowed 15 seconds to read from the text block, which consisted of fifty English words placed five rows (Figure 2). As the participant read aloud, the number of words that they read was counted for each device under each level of illuminance. The viewing distance between the reader and the device was taken simultaneously while calculating the number of words that were read during the allotted time period for each device. The subjects were never told how many words they actually read for each test.

BOY	CAT	CAP	DOG	BOOK
BOX	GREEN	OPEN	JAPAN	MILK
APPLE	CITY	SEVEN	CAR	FISH
MAP	PEN	MAN	BAG	DESK
STOP	HOTEL	PIANO	RED	HAND
JAPAN	MILK	APPLE	CAP	DESK
OPEN	RED	DOG	SEVEN	BOY
GREEN	MAP	CAT	HOTEL	MAN
STOP	CAR	BOOK	PIANO	CITY
PEN	HAND	FISH	BOX	BAG

Figure 2 Example of reading text block.

Second, after completing each individual reading task, all subjects evaluated the devices by using the visual analogue scale (VAS). This scale system is used in questionnaires as a subjective psychometric measurement that allows subjects to provide their attitudes directly from a scale of statements. When answering, the respondents specified their level of agreement to a statement on a much wider continuous line between two end-points than is typically found on a standard 5-point Likert scale [32].

In this study, VAS required that participants rate readability of a device on a scale from 0 (Worst) to 100 (Best). Previous studies have found that it is possible to establish a baseline score of 45 to indicate whether subjects reach a sufficient level of reading of a particular text [33]. This testing configurations conformed to those suggested in the International Organization for Standardization when evaluating LCD products [34].

2.3 Results

The three tables below (2-4) provide the fundamental results of the empirical measurement of the optical system used in this experiment. These measurements used a portable brightness meter (CS-100A, Konica Minolta Inc., Japan) that can measure any light source inside or outdoor. The aim was to ascertain data on the effects of ambient illuminance on the brightness, contrast ratio, and reflection of each of the display devices.

Table 2 below shows the results of the relationship between ambient illuminance and brightness under each of the conditions. In this context, “White” signifies maximum brightness, and “Black” refers to the minimum brightness (Table 2). The results for both White and Black showed the same tendency; that is, the brightness value increased as the ambient illuminance increased for all of the display devices.

Table 3 below establishes the relationship between the ambient illuminance and contrast ratio for each of the devices. Both the contrast ratio of the EPD and paper text did not change with increases in the ambient illuminance. By contrast, both the ILU-EPD and LCD had an inverse relationship between the contrast ratio and the ambient illuminance.

Table 4 below shows the results of the relationship between the ambient illuminance and reflectance. Reflectance was calculated from the direct brightness of the light diffuser and from each device (including paper text) under each illuminance condition. The value of reflection of the White (maximum brightness) was higher than that of the Black (minimum brightness) in all ambient illuminance conditions, regardless of the display terminal. Both the reflection of EPD and paper did not change with increases in ambient illuminance, which was similar to the results in Table 3. In contrast, both the ILU-EPD and LCD had inverse relationship between the reflectance and ambient illuminance.

Table 2 Relationship between the ambient illuminance and the brightness

	EPD		ILU-EPD		LCD		Paper	
Ambient illuminance	Brightness (cd/m^2)							
	White	Black	White	Black	White	Black	White	Black
10	1.09	0.19	92.1	6.36	374	2.98	2.49	0.252
20	2.18	0.38	93.4	6.57	374	3.05	4.98	0.504
50	5.45	0.94	97.3	7.20	374	3.26	12.4	1.26
100	10.9	1.88	104	8.25	374	3.62	24.9	2.52
150	16.4	2.82	110	9.30	374	3.97	37.3	3.78
200	21.8	3.76	117	10.4	375	4.33	49.8	5.04
300	32.7	5.64	130	12.5	375	5.04	74.6	7.56
500	54.5	9.40	156	16.7	376	6.46	124	12.6
750	81.8	14.1	188	21.9	378	8.23	187	18.9
1,000	109	18.8	220	27.2	379	10.0	249	25.2
1,500	164	28.2	285	37.7	382	13.6	373	37.8
2,000	218	37.6	350	48.2	385	17.1	498	50.4
5,000	545	94.0	739	111	403	38.4	1244	126
8,000	872	150	1128	174	421	59.7	1990	202

White. means maximum brightness, and black means minimum brightness.

Table 3 Relationship between the ambient illuminance and the contrast ratio

	EPD	ILU-EPD	LCD	Paper
Ambient illuminance	Contrast ratio[1)]			
10	5.80	14.8	125	9.87
20	5.80	14.5	122	9.87
50	5.80	14.2	115	9.87
100	5.80	13.5	103	9.87
150	5.80	12.6	94.2	9.87
200	5.80	11.9	86.6	9.87
300	5.80	11.3	74.5	9.87
500	5.80	10.4	58.3	9.87
750	5.80	9.34	45.9	9.87
1,000	5.80	8.58	37.9	9.87
1,500	5.80	8.12	28.2	9.87
2,000	5.80	7.57	22.5	9.87
5,000	5.80	7.27	10.5	9.87
8,000	5.80	6.65	7.05	9.87

1) Each contrast ratio was calculated from both mesured maxmum and minimum brightness values under each ambient illuminance condition.

Table 4 Relationship between the ambient illuminance and the reflection

	EPD		ILU-EPD		LCD		Paper	
Ambient illuminance	Reflectance							
	White	Black	White	Black	White	Black	White	Black
10	0.05	0.009	4.53	0.313	18.37	0.15	0.12	0.012
20	0.05	0.009	2.30	0.162	9.19	0.075	0.12	0.012
50	0.05	0.009	0.96	0.071	3.68	0.032	0.12	0.012
100	0.05	0.009	0.51	0.041	1.84	0.018	0.12	0.012
150	0.05	0.009	0.36	0.031	1.23	0.013	0.12	0.012
200	0.05	0.009	0.29	0.025	0.92	0.011	0.12	0.012
300	0.05	0.009	0.21	0.020	0.62	0.008	0.12	0.012
500	0.05	0.009	0.15	0.016	0.37	0.006	0.12	0.012
750	0.05	0.009	0.12	0.014	0.25	0.005	0.12	0.012
1,000	0.05	0.009	0.11	0.013	0.19	0.005	0.12	0.012
1,500	0.05	0.009	0.09	0.012	0.13	0.004	0.12	0.012
2,000	0.05	0.009	0.09	0.012	0.09	0.004	0.12	0.012
5,000	0.05	0.009	0.07	0.011	0.04	0.004	0.12	0.012
8,000	0.05	0.009	0.07	0.011	0.03	0.004	0.12	0.012

White. means maximum brightness, and black means minimum brightness.

The main purpose of this experiment was to have subjects compare and evaluate readings from an ILU-EPD, EPD, LCD and paper text under 14 levels of ambient illuminance. Figure 3 and Table 5 below represent part of the objective measurements for the reading tasks. The figure illustrates the number of words that each subject read in a short duration of 15 seconds for each of the 14 levels of illuminance (Figure 3). Below 300 *lx*, the subjects were able to read more words with the iPad relative to the other devices, especially compared to the Kindle DX. All the devices had similar word counts between 200-750 *lx* (Table 5). However, after this level, the positions of the iPad and Kindle DX were reversed.

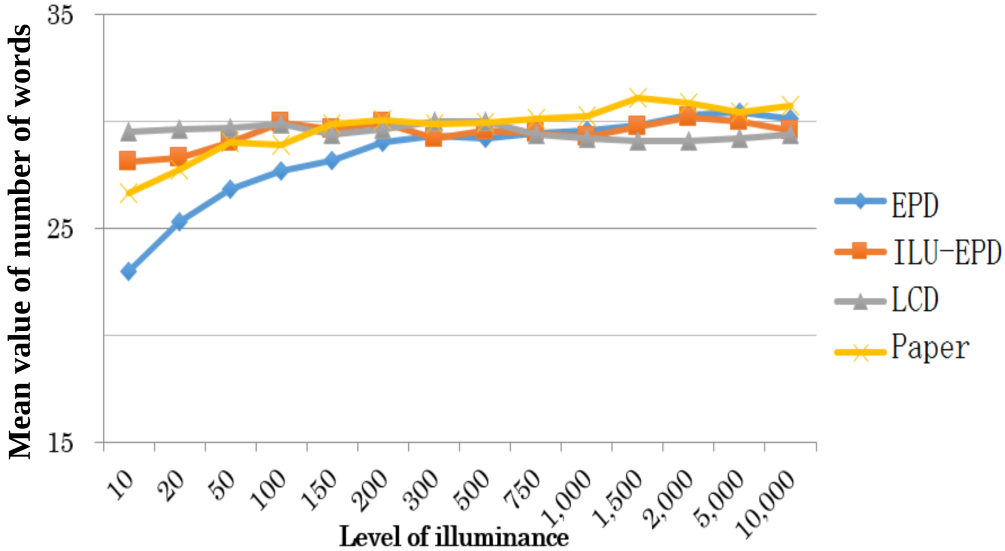

Figure 3 Mean value of words read in 15 seconds by illuminance level.

Table 5 Mean value of number of words read

	EPD Mean±S.D	ILU-EPD Mean ± S.D	LCD Mean ± S.D	Paper Mean ± S.D
10 lx	23.0 ± 9.20	28.1 ± 7.59	29.5 ± 6.92	26.7 ± 7.12
20 lx	25.3 ± 7.84	28.3 ± 6.91	29.6 ± 6.77	27.7 ± 6.22
50 lx	26.8 ± 7.04	29.1 ± 6.45	29.7 ± 6.39	29.0 ± 6.68
100 lx	27.7 ± 6.62	30.0 ± 6.43	29.9 ± 6.02	28.9 ± 6.04
150 lx	28.2 ± 6.33	29.7 ± 6.26	29.4 ± 5.90	29.9 ± 6.46
200 lx	29.0 ± 6.96	29.9 ± 6.46	29.7 ± 5.79	30.1 ± 6.53
300 lx	29.3 ± 6.64	29.2 ± 6.10	30.0 ± 6.09	29.9 ± 6.26
500 lx	29.2 ± 6.34	29.6 ± 6.41	30.0 ± 6.21	30.0 ± 5.95
750 lx	29.5 ± 6.10	29.4 ± 6.50	29.4 ± 6.25	30.2 ± 5.95
1,000 lx	29.6 ± 6.29	29.3 ± 6.48	29.2 ± 6.25	30.3 ± 5.86
1,500 lx	29.8 ± 6.22	29.8 ± 6.27	29.1 ± 6.43	31.1 ± 6.76
2,000 lx	30.3 ± 6.40	30.2 ± 6.45	29.1 ± 6.21	30.9 ± 6.39
5,000 lx	30.4 ± 6.45	30.0 ± 6.13	29.2 ± 6.03	30.5 ± 6.45
10,000 lx	30.2 ± 6.38	29.6 ± 6.34	29.4 ± 6.70	30.7 ± 6.19

Figure 4 below shows a graph from the results of the subject's evaluations (VAS) for each device under 14 different conditions of illuminance. Table 6 below provides the data for the mean values from the evaluations. As the graph indicates, all the VDT's were evaluated as sufficiently readable between levels of 300-500 *lx* (Figure 4). The evaluations found that at the lower levels of ambient illuminance (below 150-200 *lx*) reading was difficult for the ILU-EPD, EPD, and conventional paper compared to the ratings of the LCD. However, the evaluations for these devices improved until about the 500 level when the ratings tapered off for the ILU-EPD and EPD at higher levels of illuminance (Table 6).

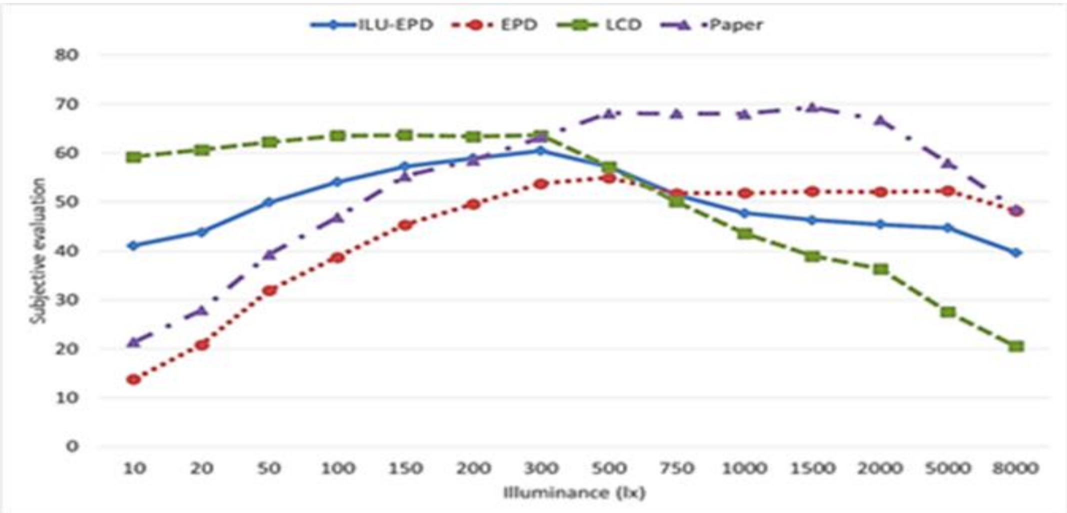

Figure 4 Subjective Evaluation of the devices.

Table 6 Mean value of subjective evaluations

	EPD Mean±S.D	ILU-EPD Mean ± S.D	LCD Mean ± S.D	Paper Mean ± S.D
10 lx	13.8 ± 15.81	41.1 ± 22.48	59.3 ± 23.23	21.4 ± 18.43
20 lx	20.8 ± 16.79	43.9 ± 20.55	60.6 ± 20.10	27.9 ± 18.74
50 lx	32.0 ± 18.68	49.9 ± 18.92	62.3 ± 19.38	39.3 ± 18.49
100 lx	38.8 ± 19.16	54.1 ± 17.63	63.5 ± 17.62	46.9 ± 17.76
150 lx	45.4 ± 19.63	57.3 ± 17.95	63.7 ± 17.59	55.3 ± 16.92
200 lx	49.6 ± 19.18	59.0 ± 17.62	63.4 ± 16.50	58.6 ± 17.34
300 lx	53.8 ± 19.30	60.5 ± 18.44	63.6 ± 17.47	63.2 ± 18.04
500 lx	55.0 ± 20.85	57.2 ± 22.74	57.3 ± 21.91	74.0 ± 19.97
750 lx	51.8 ± 19.71	51.4 ± 20.23	50.0 ± 20.68	68.1 ± 18.14
1,000 lx	51.8 ± 21.22	47.8 ± 20.66	43.6 ± 21.93	68.0 ± 20.20
1,500 lx	52.2 ± 22.19	46.3 ± 22.20	39.0 ± 23.24	69.3 ± 20.32
2,000 lx	52.1 ± 23.71	45.4 ± 23.03	36.4 ± 24.11	66.8 ± 22.31
5,000 lx	52.3 ± 26.43	44.7 ± 24.98	27.5 ± 24.54	58.0 ± 26.39
10,000 lx	48.2 ± 29.76	39.7 ± 28.37	20.5 ± 21.45	48.6 ± 29.59

2.4 Discussion

This experiment looked at how well three terminal devices performed under 14 levels of ambient illuminance. The readers evaluated the readability of an ILU-EDP, EDP, LCD, and paper text under the different levels after carrying out a specific reading task. This required the participants to read as many words as possible within a 15 second period. As mentioned, one of the crucial differences between a backlit LCD and e-paper is the performance of the screen under different lighting. The former type includes a self-illuminating display system, while the latter has a reflective one. Thus, both devices show different visibilities, and the difference in illumination affects legibility and readability.

As manufacturers of the two display technologies continue to compete in their respective markets more concern has been on costs and functionality. Local markets tend to attract a different level of consumer interests in such products, and tablets led in sales in Japan and the US until about 2006. Initially, e-paper devices were restricted in terms of functional capabilities and were aimed at those individuals interested in building a library of e-books and periodicals. This becomes apparent when comparing the ratings of the EPD (Kindle DX) to other devices. In this experiment, the readers rated the EPD as more difficult to read relative to the other terminals even between 300-500 *lx*. Furthermore, while the evaluations of the EPD surpassed the other mechanical devices after 750 *lx*, the ratings for paper text remained far greater.

The introduction of the ILU-EPD (PW) with a front light in 2007 decreased the gap between the two VDT screen performances. The addition of the front light helps at lower levels of illuminance but hampers the device at the higher levels. The results in this study indicate that the ILU-EPD performed closer to the LCD terminal when compared to paper at the different levels of illuminance. However, like the LCD, the ILU-EPD appears to lose its advantage relative to paper text after the 500 lx level.

Some studies have indicated that consumer demand may be more concerned with costs versus functionality rather than issues related to lighting ambience [35]. As of 2013, market research in Japan indicated that the sales of tablets were three times higher than that of e-readers with only 8% of Japanese readers having downloaded an e-book compared to 20% in the United States [36]. In general, Japanese readers still prefer bookstores and find that tablets offer more available forms of content than e-paper devices.

However, consumers are less knowledgeable about the differences between the display technologies or their performance capabilities though they are able to grasp the contrasts between actual functionality of a device [37]. Meanwhile, government agencies, academia, and research in manufacturing continues to study the safety and the performance of such technology as well as to verify the claims of the industry with respect to claims about the products, particularly when it comes to the performance of the screens under different conditions of lighting.

Much of the literature indicates that under conditions of high illuminance, readability of the self-illuminating display (LCD) is poor due to glare, particularly in outdoor sunlight [29] [38]. On the contrary, readability of a reflective display (EPD) appears to perform closer to paper text when read under similar conditions. The introduction of the integrated lighting unit (ILU-EPD) in 2007 represented a form of hybrid between the previous two display technologies. This display behaves similar to a self-lighting type under low illuminance, but like the reflective type under high illuminance.

Under controlled levels of ambient illuminance, 110 subjects found that the LCD (iPad) was more readable at the lower levels, especially below 300 *lx*. In contrast, the readers found the EPD (Kindle DX) and paper text difficult to read until the 200 *lx*, surpassing the LCD at about 500 *lx*. Though the number of words read for all devices did not decrease after the 500 *lx* level, the subjective evaluations of these three devices did decrease, particularly relative to paper. Furthermore, in terms of the ratings, there was a major change in how the participants evaluated the three mechanical devices.

While the number of words read per 15 seconds was fairly similar for the LCD, the readers read less words for the EPD below the 500 *lx* level. The results from this experiment show that the ILU-EPD (PW) can sustain readability under low illuminance conditions in comparison with the EPD, and conventional paper text. Under conditions of illuminance of less than 300 *lx*, the participants evaluated the ILU-EPD (PW) significantly higher than the EPD (Kindle DX). This matches Shen *et al.* who also found that under illuminance of more than 750 *lx*, the reader's evaluation of ILU-EPD was worse than for the EPD [39].

The contrast ratios for the EPD and Paper remained the same regardless of the changes in the level of ambient illuminance, and the increasingly favorable evaluations these two terminals surpassed the ratings of the other two devices at about 400 *lx* (Figure 4). The advantages of the backlight (LCD) and front light (ILU-EPD) are off-set as the illuminance levels increase. As brightness increases, the black elements appear grayer and the contrast ratios decrease. As a result, when the back and front lights fall below the ambient light, the readability drops sharply.

In sum, the readers in this experiment evaluated all four forms of displays nearly equal in terms sufficiently readable between 200-500 *lx*. The VDTs with backlit or some form of integrated light unit were more readable at lower levels of illuminance compared to reflective displays. As expected, the evaluations for the LCD (iPad) were higher at lower levels of illuminance but dropped after the 500 *lx* level, while the reverse was true for the reflective device (Kindle DX) [40]. As with other studies, the evaluations of the reading of conventional paper increased until the 2000 *lx* [41].

The trend was reversed between 500-750 *lx*, when participants found the reflective type displays more readable. The limitation in this experiment was that the objective measurement was of a short duration due to the large number of readings required to meet the needs of the 14 different levels of ambient illuminance. Po-Chung *et al* have suggested that measurements of a longer duration that look at cognitive performance and visual fatigue are needed in order to better comprehend how these VDTs affect readers under different lighting conditions [42].

2.5 Conclusions

In terms of ergonomic considerations, the total data collected from both the objective and subjective measurements in this experiments can be summarized into two points with regard of the use of VDTs. First, a recommended minimum illuminance for comfortable reading of all VDTs should be set at 200 *lx*. Second, an LCD and ILU-EPD have a positive effect for enhancing readability under low ambient illuminance.

Chapter 3: The Effects of Font Sizes and Aging on the Readability of E-paper Devices

3.1 Introduction

The previous chapter addressed the effects of an environmental condition, ambient illuminance, on the readability of several electronic devices. This chapter looks at one facet of visual performance on the readability of electronic papers. The chapter provides the results from an experiment that analyzed how different age groups evaluated the readability of different VDTs performed in delivering one specific font type.

Though conventional forms of print such as books, magazines, and newspapers have a relatively long history, the introduction and development of electronic print has only emerged over the last few decades. The interest and consumption of the large number of types of VDTs has spurred a race in innovative screen development that attempts to mimic traditional paper text as close as possible. The success and spread of mechanical reading device has expanded to all ages; however, questions have arisen regarding the manufacturers claims that their products are similar to conventional paper.

Though electronic paper may take decades to replace traditional paper sources, many issues still exist in terms of the digital presentation of reading materials on a screen format. In ergonomics, individual reading can be measured as an outcome or as a process. In terms of outcome measures, a researcher might look at variables associated with visual fatigue, comprehension, reading speed, or accuracy. For process measures, the investigator might focus on how individuals use or manipulate the text and include such concerns as image polarity, contrast ratios, the visual angle, and display characters (fonts).

The experiment presented in this chapter may appear linked to an outcome approach because it includes tests related to reading speed and accuracy. However, the measurement tasks are ancillary to the primary aim associated with how different age groups visually work with smaller font sizes. In this experiment, participants of different ages took a silent reading test to evaluate the readability of three different font sizes used on three displays. The aim was to focus on what was the minimum font size that the various ages of the participants could maintain in their reading performance; that is, testing to see that there was no significant decrease in reading speed and a correct answer rate. In addition, the study sought to evaluate to what degree e-paper devices matched the functionality of paper text as claimed by manufacturers.

3.2 Methods

3.2.1 Participants

The participants for this experiment included 99 males and females between the ages of 15 to 76 years old (M 46.7, SD 14.7). Participants who typically wore correct lenses of any type were allowed to use them for all stages of the experiment. The readers were checked for severity of lens cloudiness or cataracts. The tables below provides the data from which appropriate groupings were made for the experiment.

Table 7 below shows the number of participants divided into age groups. The participants were divided into four groups according to the following age association young (29 years and younger), middle-aged (30 to 44 years old), senior middle-aged (45 to 64 years old), and elderly (65 years and older). Following this step, the individuals were then checked for the degree of cataract cloudiness.

Table 7 Participants divided by age group

	Young	Middle	Senior Middle	Elderly	Total
Exp	15	24	44	16	99

An Anterior Eye Segment Analysis System (NIDEK EAS-1000) was used to measure the amount of lens cloudiness in the reader’s eyes. Table 8 below shows the measured values of the readers divided according to the established age groups. Typically, the gradation or range of cloudiness is ranked from zero (perfectly clear) to 255 (extreme cloudiness). As the table shows, the youngest group had sufficient amplitude of lens accommodation. The middle-aged group had sufficient near vision ability, although their accommodation was slightly weaker. The senior middle-aged group had mild presbyopia and problems with near vision work (Table 8). The elderly group had typical presbyopia and generally had to wear glasses for close vision.

Table 8 Participant lens cloudiness

	Young Mean±S.D	Middle Mean±S.D	Senior Middle Mean±S.D	Elderly Mean±S.D
Exp.	46.0±10.0	69.1±21.3	93.3±21.6	148.8±36.6

† The range of cloudiness gradation is 0 to 255

3.2.2 Experimental design

This experiment included a comparison of three types of reading terminal devices, an e-paper (Amazon Kindle DeluxeTM), a backlit LCD (Apple iPadTM), and as a reference, conventional paper text (with the text printed on PPC paper of 69% whiteness) [43] [44]. In this chapter, the Kindle Deluxe is referred to as DX, the Apple iPad as iPad, and the conventional paper as Paper. Table 9 below provides the technical details for each device. The resolution for electronic devices are typically measured in pixel-per-inch while paper is measured in dots-per-inch (Table 9). This difference is a relevant issue because it relates to questions associated with the actual size of fonts and their comparison.

Table 9 Device specifications

	DX	iPad	Paper
Screen size	9.7 inch	9.7	6 inch
Resolution	150 ppi	264 ppi	1200 dpi

Kent paper was used to hide the type of device in order to reduce the chance of any bias due to brand recognition. The test screen or test paper was mounted on the center of a board. The text displayed on each medium was set at the same height. The backlight level of the iPad was set to maximum levels. The text color was black/dark, and the background color was white/bright.

Figure 5 below provides a bar-graph of the screen luminance for each device. The DX showed results on the screen luminance similar to conventional Paper, while the iPad was distinctly different (Figure 5). For this experiment, the contrast ratios were taken from the measured values of the brightness of the background color and text color (Figure 6). The iPad had a higher contrast ratio compared to the other devices because it showed a lower screen luminance of black/dark and a higher screen luminance of white/bright.

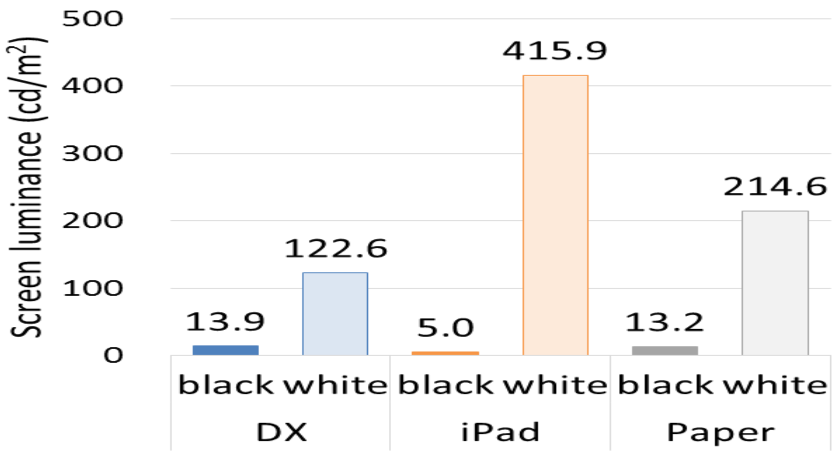

Figure 5 The screen luminance of the black letter on the white background.

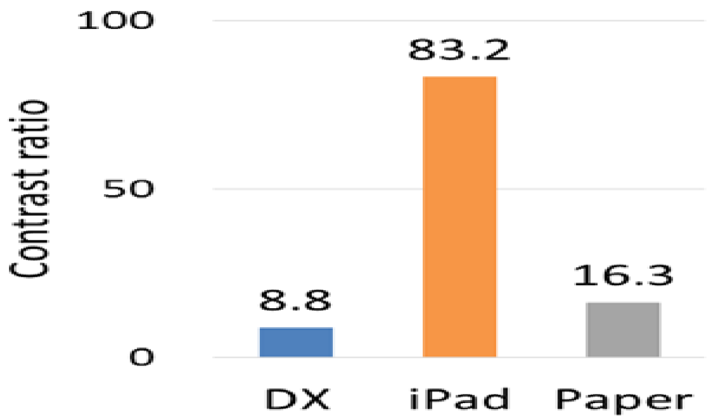

Figure 6 The contrast ratio of each device.

All of the reading devices were placed into a compartmental lighting system that was set on a desk within a darkened room (Figure 7). The lightning system for this experiment was created with reference to a previous study [45]. All the experimental tasks were carried out at precisely 942 *lx* using a 6500 K-LED light source with a fluorescent lamp that had a uniform color temperature. The ISO suggests an illuminance level of 1,000 *lx* for doing precision work in an office [46], so the procedure for setting up the lighting conformed to this recommendation. The headrest for the participant's forehead was kept at a visual distance of 400 mm. The participants viewed the displays at an angle of about 100 degrees to eliminate any problems with self-reflection that might occur on the screens of the mechanical devices.

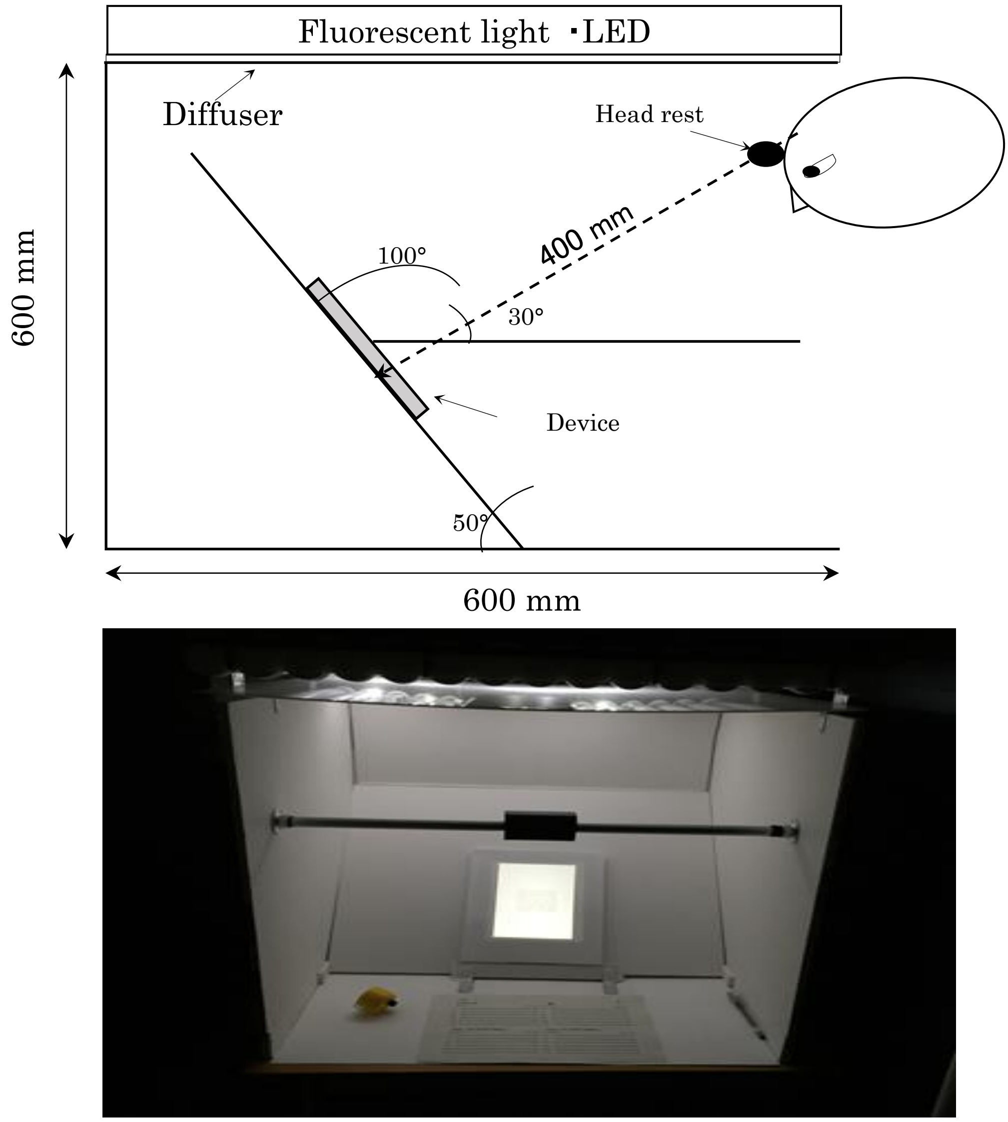

Figure 7 The setup for the reading compartment

3.2.3 Task design

The experimental tasks involved a block reading test of a short duration (Figure 8). The display format conformed to that used for evaluation of electronic display devices by the International Organization for Standardization (ISO) [47]. In this experiment, random Latin alphanumeric letters with a unified size of characters were used for the readings rather than words. The font type was Courier for this experiment because it is a uniform monospaced font that has a slight serif. A monospaced font is one with a fixed width as each letters occupies the same amount of horizontal space making it a good standard choice for objective measurements [48]. As the width of the characters for Courier is uniform, the focus was with the height of the font size. Thus, for this experiment, the font sizes were set at 8 pt (approx. 2.75 mm height), 12 pt (3.25 mm), and 16 pt (5.75 mm).

```
LcBs ENckC gplY ELOjPxasTPtAxa
hQ mpU cq VwFdihGamGMztI sj ov
mn KCU QNY hoGqw oS Fa DmsUiLG
BDIqUrGx gLfdaehwd XNj ELdP tL
wYsfmlQa USIg xb BavcTslj QBFv
dK Mb tBH FNcLjY lqZrZN GfrdjC
XSlL NdyTt sa XH wCIIcT rernDq
IEDr vJBpc RvibD LdzY QXb NqEI
kUx zMkm JSxg wmHGF Ltw AOkPjd
BtT xzjT YAI bjYHII AQ vQa Goh
bY nlZ uiVPGzP SZf pH nrzv jDa
tqBBpkRmv QqX AjMGzoJBOrvpKrCZ
Ecwgo zJ ZdyObJn YOz PDBOmzneT
aOe sdNlDL SrysCAcmxbTrMQ sRmA
```

Figure 8 Example of text block for reading task.

Figure 8 above provides an example of a text block used in the reading tasks. For this study, the readers performed nine tests (three font sizes per each of the three devices). As the participants read a text silently from the top left, they were timed for completion. While the readers went through the text, they were asked to count the number of capital letter “M”s in a block with a mechanical counter while being timed. Thus, the correct answer rate was calculated from the number “M”s that the participants found from the actual number of “M”s in the text. The correct answer rate was not entirely exact because the participants sometimes misread other alpha characters as large “M”s.

The reading time index and correct answer rate index were divided by the average values of each of the participant’s actual values in order to standardize their performance. A high-scoring reading time index meant that a participant required a long time to read through a block. The high scoring correct answer rate index meant that there was a large number of correct answers.

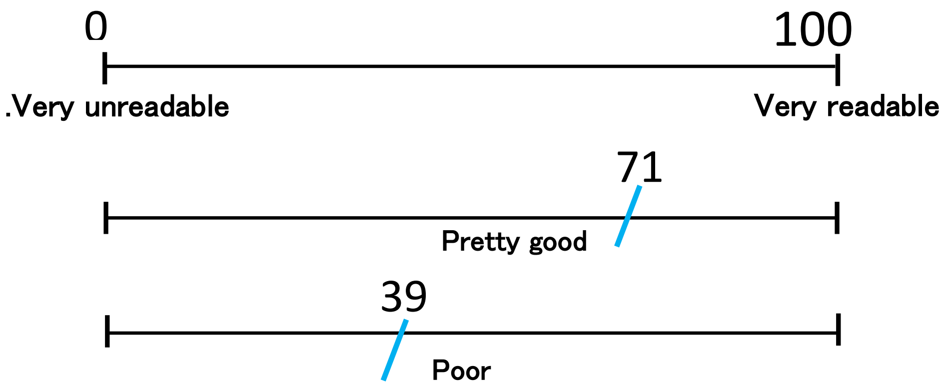

Figure 9 Example of evaluations by VAS.

After each reading, the participants also evaluated the readability of the texts using a Visual Analog Scale (VAS). The values of the VAS were converted into a 100 point scale in the final analysis. Figure 9 above illustrates how the subjective evaluation in the VAS actually scored the results. A high-score on the VAS meant that a device was very readable according to a participant (Figure 9). Typically, scores of 0 occur when readers cannot read something or when the reading time or answer rate cannot be scored;

however, no such problems occurred in this experiment.

Finally, a two-way analysis of variance (two-way ANOVA) was employed as a statistical method to evaluate the total results. As this also involved an age-grouped analysis, a one-way analysis of variance (ANOVA) and the Scheffé multiple comparison procedure were used to adjust to significant levels in the linear regression.

3.3 Results

Table 10 below shows the results from the two-way ANOVA for the participants' evaluation (VAS), reading time index, and correct answer rate index. The VAS showed significant differences among both types of devices and the font sizes. No two-factor interaction was observed among these fonts. For the reading time index, no significant differences were observed among the types of device and the font sizes. The correct answer rate index showed significant differences among the font sizes (Table 10).

Table 10 Two-way ANOVA for the VAS and the reading time and correct answer indices

Source	Df	SS	MS	*F*	
VAS					
Types of devices(D)	2	7030.47	3515.23	7.94	**
Character sizes(C)	2	84091.96	42045.98	94.96	**
D×C	4	174.48	43.62	0.10	
Reading time index					
Types of devices(D)	2	0.004	0.002	0.226	
Character sizes(C)	2	0.001	0.000	0.028	
D×C	4	0.045	0.011	1.163	
Correct answer rate index					
Types of devices(D)	2	0.032	0.016	0.851	
Character sizes(C)	2	0.330	0.165	8.732	**
D×C	4	0.404	0.101	5.334	

† **; $p<0.01$

Table 11 below shows the multiple comparisons between the VAS and correct answer rate index. The VAS scores for 8 pt (app. 2.75 mm) were significantly lower compared to the larger font sizes. The VAS scores for the DX were significantly lower than those of the iPad and Paper. The correct answer rate indices for the 8 pt size were significantly lower than those of more than 12 pt (3.25 mm) size. As the table shows, the values in the same column with the same letters are significantly different (**; p<0.01, *; p<0.05). For example, 8 pt and 12 pt in the participants' evaluation column are assigned the letter ‘a’, which means that the subjective evaluation of 12 pt character size is significantly better than that of 8 pt (Table 11).

Table 11 Multiple comparison for the VAS and correct answer rate index

	VAS (Mean±S.D.)		Correct answer rate index (Mean±S.D.)	
Character size				
8 pt	45.9 ± 21.8	a**, b*	0.973 ± 0.161	a**, b**
12 pt	63.9 ± 19.5	a**	1.018 ± 0.122	a**
16 pt	68.4 ± 22.0	b*	1.009 ± 0.130	b**
Type of device				
DX	55.7 ± 22.9	a**, b*		
iPad	62.5 ± 23.3	a**		
Paper	60.0 ± 23.1	b*		

Table 12 below shows a comparison of the VAS by the font sizes for each age group using the one-way ANOVA. The VAS scores for the DX at 12 pt size were significantly lower than for the iPad. Here, the values in the same column with the same letters are significantly different (*; p<0.05) using ANOVA and the Scheffé multiple comparison procedure. For example, DX and iPad in the 12 pt column are given the letter 'a', which means that the subjective evaluation of iPad device is significantly better than that of DX (Table 12).

Table 12 Subjects' evaluations using three devices under three character sizes

	1_8 pt (Mean±S.D.)	2_12 pt (Mean±S.D.)		3_16 pt (Mean±S.D.)
DX	42.6 ± 22.1	60.3 ± 19.0	a*	64.3 ± 21.2
iPad	49.4 ± 21.0	67.1 ± 19.3	a*	71.1 ± 23.5
Paper	45.8 ± 21.8	64.4 ± 19.7		69.8 ± 20.5

Table 13 below shows a comparison of the correct answer rate index by the font sizes for each age group using the one-way ANOVA. The VAS scores for the iPad at 12 pt size were significantly lower than that of the Paper. No significant difference for the reading time index was observed between the font sizes and types of devices. Finally, no significant difference for all indices were observed among the age groups. In this table, values in the same column with the same letters are significantly different (*; $p<0.05$) using the ANOVA and the Scheffe multiple comparison procedures (Table 13).

Table 13 Multiple comparison for VAS, reading time index and correct answer rate index

	1_8 pt (Mean±S.D.)		2_12 pt (Mean±S.D.)	3_16 pt (Mean±S.D.)	
DX	1.014 ± 0.151		0.967 ± 0.116	1.044 ± 0.101	
iPad	0.936 ± 0.125	a*	1.025 ± 0.071	1.058 ± 0.095	a*
Paper	0.947 ± 0.173	a*	0.988 ± 0.117	1.021 ± 0.100	a*

3.4 Discussion

The ISO recommends more than a level of 500 *lx* for indoor reading of all types [45] and up to 1000 lx for a working environment. Some studies have found no significant differences on the readability of an e-paper, LCD, or paper at the 1,000 *lx* level [14]. This experiment was conducted just under 1,000 lx of illuminance to eliminate the effect of ambient illuminance on the readability of the reading terminals.

In traditional typography involving paper text, point size generally refers to height and width of a block on which a character rests rather than the actual letter. Thus, while two fonts can have the same point size, the letters themselves could be comparatively different in terms of height and width which in turn can affect spacing at the lower sizes. Therefore, a uniform font type such as Courier was applied in this experiment.

The Courier font type represents a monospaced font recommended for such studies by the ISO [46]. Moreover, some studies have reported that Courier is a viable font for the elderly suffering with vision problems including macular degeneration [49]. As a result, Courier serves as a type standard in which the character heights in millimeters ensures compatibility with an objective measure.

The main purpose in this experiment was on the visual performance of the font features as a display media and how they may effect readability for various ages. A comparison was made between the e-paper and LCD, which are currently available on the market, with conventional paper text. Previous studies assisted in order to establish the ideal text font sizes [50] [51], which were in turn set at three levels: 8 pt (character height: 2.75 mm), 12 pt (3.25 mm), 16 pt (5.75 mm).

The reader evaluations showed scores above 45 (on a scale 0 to 100) for each device and font size on the Visual Analytical Scale, with exception of the DX at the 8 pt size. The mean average score for the DX was slightly under 45 on the scale. Past studies have reported establishing a baseline score of 45 for VAS to indicate whether participants reached a certain level of proficiency in reading a text [32].

The e-paper showed no significant difference compared with other devices for the reading time index and correct answer index. No significant differences for each character size were observed among age groups. All the devices were readable at about the 8 point size which supports previous studies that looked at visual performance and fatigue [52] [53]. In total, the results suggest that the height size of Courier at 8 pt could represent a default setting for such devices.

3.5 Conclusions

This study investigated the effects of ambient illuminance, font sizes and aging on the readability of e-papers. The findings for this experiment offers several suggestions with respect to font sizes and the devices, and how they might be used by the elderly.

3.5.1 Font sizes

(1) The screen font size (character height) that participants feel readable is more than 2.75 mm. A font size of more than 2.75 mm is recommended as a permissive size to be displayed on the screens of e-papers for all ages.

(2) The minimum font size level at which those readers under 65 years of age can maintain their performance (that is, there is no decrease in reading speed and correct answer rate) is the character height size of 2 mm. While those over 65 will see a decrease in performance at below 2.75 mm.

(3) All groups saw a decrease in reading speed at the 2.75 mm (8 pt), which explains the rationale for recommending this size as the minimum limit.

3.5.2 Devices

(1) The readability of electronic devices used in this study performed equally to paper text. However, such devices are more advantageous because they allow the reader the opportunity to change font sizes, and this is particularly helpful to the elderly.

Chapter 4: Effects of Aging and Visual Acuity on the Legible Point Size of a Single Character on an E-paper Display

4.1 Introduction

The previous two chapters described experiments that investigated the effects of lighting (environmental condition) and font size (performance) on the readability of different electronic devices. This chapter presents an experiment that analyzed human factors (visual acuity, aging and lens cloudiness) on the legibility of two font types displayed on an e-paper. In simplest terms, legibility refers to the ability to recognize and identify characters or fonts, while readability is more related to determining what the characters actually make-up in terms of meaning or comprehension [54]. The legibility of characters or fonts can have a direct affect upon readability.

Meanwhile, visual acuity refers to the clarity of vision and is a measure of the spatial resolution that human beings have as part of the visual processing system and is typically tested with a Snellen Chart or Landolt rings (as well as other tests) [55]. Both distance and size of viewing characters are relevant in terms of establishing what might be tested or set as a standard. Ideally, a person with 50cm/50cm vision (reading from a book or screen device) would be able to discern characters on the display from 50 cm and therefore would be expressed as having 1.0 acuity. Both viewing distance and aging play a role on visual acuity, which has been well documented in the literature [56] [57] [58].

In 2013, the estimated world expenditure that consumers spent on books was $121.5 billion, and business forecasters predicted that the total spent on such items would probably plateau at about 1.1% by 2018 [59]. Meanwhile, the total amount spent on for e-books represented only about 12% of the book market in the fiscal year 2013-14 but the prediction has been that this would increase to 25% by 2018 [60]. While older people may still have some reluctance about buying and reading e-paper devices, a shift in attitude may occur as this area of the market becomes more familiar with the advantages of the technology. Indeed, an increasing number of reports are indicating that such devices may actually be better for the elderly than typical books [61].

One of the concerns for all readers has been with the reading of characters on small screens with low resolution displays. Since 2007, Amazon’s e-paper products such as Kindle Paperwhite have grown in popularity. One of the reasons for this growing appeal has been due to the improvement in the device’s resolution, going from 167 ppi to 300 ppi, and at a lower price. While e-paper devices have become increasingly popular, they include numerous font types with multiple sizes that need testing for legibility. Therefore, the aim of this experiment was to compare and evaluate the smallest point sizes that could be read from two main font types: Helvetica and Times New Roman.

4.2 Methods

This study included the participation of 133 people aged 17 to 79 years old. Individuals who needed to wear corrective lens during the procedure were allowed to do so in order to complete the tests. All participants, regardless of whether or not they needed corrective lenses, were measured for binocular near visual acuity for 50 cm [60]. The near visual acuity was expressed in the following way: 0.1, 0.3, 0.5, 0.7, 1.0, or 1.2. The visual function of a single eye with cataract cloudiness (CC) in the lens [62] [63] [64] was calculated with the use of an anterior ocular segment measuring instrument called the EAS-1000^{TM} (NIDEK Inc.). There were 256 levels of cataract cloudiness (0= no cloudiness and 255=the maximum) [65]. An individual's level of cloudiness was based on the lens clarity in the best eye; for example, if a person had a level 100 in the left eye and 150 in the right eye, then they were considered as having a 100 for cloudiness.

The VDT used for this experiment was the Amazon Paperwhite. This device has a screen size of 6 inches and a resolution of 300 ppi [66]. The illuminance level was set at 750 *lx* as recommended by the International Organization for Standardization (ISO) [45] and the Japan Industrial Standards (JIS) which recommends higher than 500 *lx* for reading books [67].

Figure 10 below represents a photo of the experimental room and general reading condition. Figure 11 below presents an example of the Kindle Paperwhite displaying characters. Figure 12 below shows how the readers would have viewed the task performance.

Figure 10 Photo of the ongoing experiment.

Figure 11 Photo of the e-paper device displaying characters.

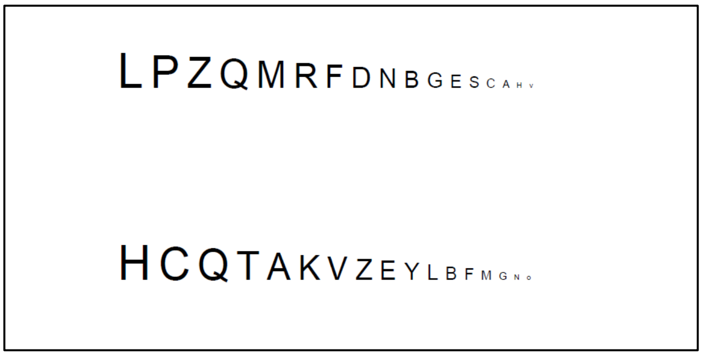

Figure 12 Example of the reading tasks of characters from largest to smallest.

The participants were asked to read a string of English alphabetic letters out loud for the same reason as the first experiment. There were 20 lines and each line contained a random selection of seventeen English letters in upper case for both font types. Seventeen letters were displayed left to right, from 18 pt to 2 pt. While there are 26 letters in the English alphabet, the letters “I” and “J” were excluded in order to avoid confusion. The experiment included a comparison of characters representing the two main font families: Helvetica, which is a sans serif font type, and Times New Roman as a serif type (Figure 13). Stone *et al.* found these font types are sufficiently representative for a comparative analysis of legibility involving adult readers [68]

(a) Helvetica

(b) Times New Roman

Figure 13 Two fonts used in the experiment.

The participants sat down in a chair and held the reading device at a set distance. The visual distance from the eye to the device was limited to 50 cm. The participants were asked to read aloud the test letters that were displayed on the screen. Reading from left to right, the participant would start at 18 pt and read down to 2 pt. Meanwhile, the tester recorded the answers whether correct or error depending on what was read aloud.

For each font, the participants had to read twenty lines; therefore, they read a total of 40 lines for both font types. In order to exclude for the effect of ordering, each reader started with a different font type, and the letters were randomly selected. As long as the participant could read a font at 80% then it was considered legible. The definition of the smallest legibility is the specific point size where a person can read a font size correctly at 80% [69]. For example, if participant A could read 16 of 20 letters at the 4 point character size (80%) but 15 of 20 at the 3 pt size (75%), then the smallest point of legibility would have been at the 4 point size.

4.3 Results

Figures 14 and 15 below show the correlation between 50 cm visual acuity and the minimum legible font size for the Helvetia and Times New Roman. As illustrated in the figures, the results found that the smallest point of legibility for the Helvetica font was an average of 3.75 pt $\pm$ 0.95 (height 0.94 mm) and for Times New Roman 4.27 pt $\pm$ 1.08 (height 0.99 mm). This means that most of the readers with 50 cm visual acuity could not read the font size for Helvetica on average below 3.75 pt (Figure 14) and for Times New Roman below 4.27 pt (Figure 15).

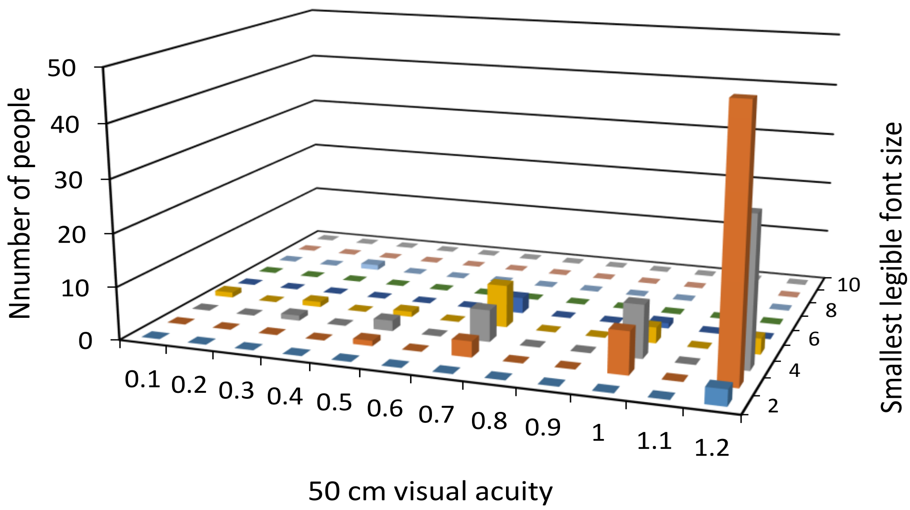

Figure 14 Correlation between visual acuity and font size for Helvetica.

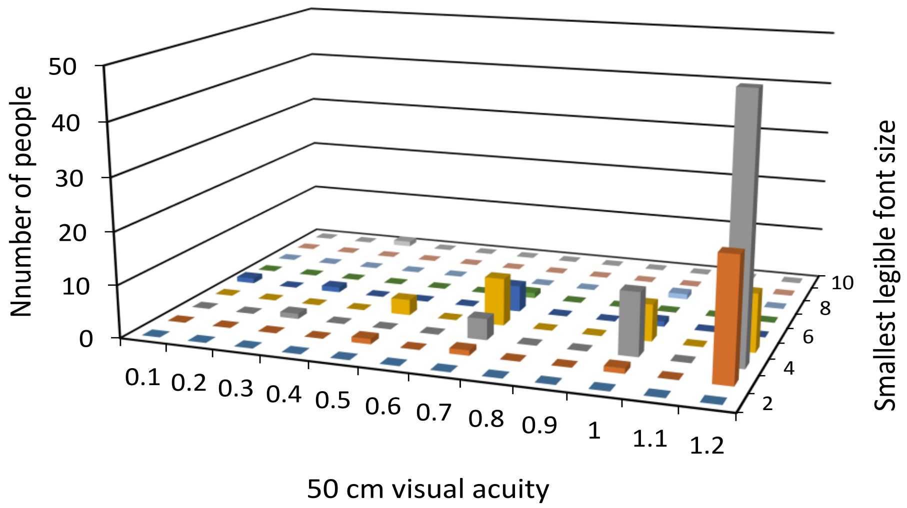

Figure 15 Correlation between visual acuity and font size at the Times New Roman.

Table 14 below provides a nonparametric correlation coefficient and comparison between the independent variables (age, 50 cm visual acuity, cataract cloudiness) and the smallest legible font sizes. As shown, the smallest legible font size had a positive correlation with age and cataract cloudiness (p<0.01) and a negative correlation with 50 cm visual acuity (p<0.01).

Table 14 Coefficient between smallest legible font size and independent variables

		The smallest legible font size above the correct response rate of 80 %	
		Helvetica	*Times New Roman*
Age (years)	Correlation Coefficient	0.438**	0.395**
	Significance (bilateral)	0.000	0.000
	Participants	133	133
Less Cataract Cloudiness	Correlation Coefficient	0.383**	0.359**
	Significance (bilateral)	0.000	0.000
	Participants	133	133
Visual acuity (Binocular)	Correlation Coefficient	-0.500**	-0.527**
	Significance (bilateral)	0.000	0.000
	Participants	133	133

**: p<0.01

After making these comparisons, 105 participants of those who had good to excellent visual acuity (above 1.0) were separated in order to serve another comparative purpose. Table 2 below provides the results from this analysis. The smallest legible characters were 3.48 ± 0.70 pt (character height: 0.88 mm) for Helvetica, and 4.00 ± 0.77 pt (0.93 mm) for Times New Roman.

Table 15 below provides a nonparametric correlation coefficient and comparison between the independent variables (age, 50 cm visual acuity, cataract cloudiness) and the smallest legible font size. As shown, for Helvetica, the smallest legible font size had a positive correlation with age and cataract cloudiness ($p<0.05$) and a negative correlation with 50 cm visual acuity ($p<0.01$). For Times New Roman, there was a negative correlation with 50 cm visual acuity ($p<0.01$).

Table 15 Coefficient of font sizes and independent variables for those with 50 cm visual acuity above 1.0

		The legible smallest font size above the correct response rate of 80 %	
		Helvetica	*Times New Roman*
Age (years)	Correlation Coefficient	0.238*	0.189
	Significance (bilateral)	0.014	0.053
	Participants	105	105
Less Cataract Cloudiness	Correlation Coefficient	0.216*	0.166
	Significance (bilateral)	0.027	0.091
	Participants	105	105
Visual acuity (Binocular)	Correlation Coefficient	-0.255**	-0.328**
	Significance (bilateral)	0.009	0.001
	Participants	105	105

*: $p<0.05$, **: $p<0.01$

4.4 Discussion

Sagawa *et al.* noted the importance of “accessible design” when dealing with technologies that may be a problem for certain groups such as the elderly [70]. Essentially, this means that assistive products can either be developed to enhance the visual performance of a VDT (with special glasses) or the device itself should be modified so as to help people with disabilities or special needs. The basic concern here in this study is with ways to modify fonts so as to better assist the elderly with the legibility of screen fonts.

The experiment included a large sampling of participants. Many of these individuals had partaken in previous human experiments for the last 10 years and were familiar with near vision experiments. Most of these individuals have appropriate glasses for 50 cm visual distance. In this experiment, the smallest point of legibility for the Helvetica font was an average of 3.75 pt + 0.95 (height 0.94 mm) and for Times New Roman 4.27 pt + 1.08 (height 0.99 mm). For these readers, the smallest font sizes were surprisingly legible. When compared to the available literature, the participants in this study were able to read font sizes half the size of most other studies. Therefore, no real recommendation can be made with regard to a minimum standard font size based on this experiment.

In general, visual acuity carries a lot of weight in the legibility of characters. The participants who had visual acuity of more than 1.0 with 50 cm binocular vision were analyzed separately in order to avoid the effects of low visual acuity. In total this group, on average, was able to legibly identify smaller font sizes. However, the legibility for Helvetica also decreased according to age while Time New Roman had a lower correlation with age.

Previous studies have reported that elderly people had lower legibility of fonts with e-papers [71] [72]. This study defined the font size by point instead of character height. With respect to the observed values, these two font styles are too small to be really legible below 3 point. The data indicates that the legibility of the smallest font of Helvetica was affected more by the independent variables, which may reflect the difference between the heights of these two typefaces. The character height of the Times New Roman is 92% of the size of a Helvetica single character. Therefore, a precise comparison of the different characters in the number of points between these two font types is difficult. In actuality, it would be better to compare these fonts according to height. The reason for this need of a different comparison is due to the fact that point size refers to the "print block" rather than the size of the character.

4.5 Conclusions

The results from this experiment revealed that age, cataract cloudiness, and 50 cm visual acuity influence the legibility of e-paper displays. Recently, e-paper displays were developed with a front light system in order to assist with indoor lighting. The contrast ratios and brightness were much improved especially for elderly people. E-ink displays are designed to be similar to conventional paper. Furthermore, e-paper devices can magnify the size of characters manually by the reader.

The results from this experiment suggest that the font type might change the legibility. However, in order to compare the various font types, a more accurate approach to looking these fonts is necessary. Further study is needed to investigate the effects of font type and character height on legibility.

Chapter V: Conclusion

Manufacturers of visual terminals, whether for home or office use, are presently attempting to produce devices that mimic the real world as close as possible. These Visual Display Terminals (VDTs) include in-built technologies on their screens such as on LCDs or e-papers. Indeed, producers of such devices seek to enhance the visual performance of their technologies while promoting the idea that such innovations are as proficient as reading from paper. As the number of products increases, consumers should consider not simply practical matters such as quality and costs but also the health and safety of such mechanical devices.

The International Organization for Standardization does attempt to establish recommended guidelines for the use of such devices. One area of concern is visual fatigue which may occur while reading such devices. Both environmental conditions such as lighting and the performance settings on mechanical reading devices can result in added strain on the eyes, which is concern of both the manufacturers as well as consumers. Therefore, the purpose of this dissertation was to provide the results from three separate studies looking at how participants handled certain tasks under different lighting conditions, several font styles (Courier, Helvetica and Times New Roman), as well as how visual acuity may affect legibility of an electronic device.

The first experiment asked subjects to evaluate three different types of electronic displays after a short reading duration under 14 levels of illuminance. The results from this first study found that a recommended minimum illuminance for comfortable reading for all electronic devices was at the level of 200 lx. Moreover, devices with additional light sourcing (LCD and ILU-EPD) showed a positive effect for enhancing readability under low ambient illuminance, while a reflective device (EPD) performed closer to paper in higher levels of illuminance.

The second investigated the effects of ambient illuminance, font sizes and aging on the readability of e-papers. The experiment used Courier as it is repudiated to be a good font type for objective measurements and generally preferred for individuals with failing eye sight. The results from the experiment found that readers under 65 years of age could read characters fairly well at about the 2 mm height range, while those of over 65 years of age began to slow their reading speed and increase the number of errors at a character height of about 2.75 mm (8 pt). As all groups began to slow their reading speed at about the 2.75 mm height, a recommended permissive setting for font sizes in electronic devices would be at this size. Furthermore, the readability of e-papers showed equal performance to paper text, but such devices are more advantageous for individuals because the font size can be manually controlled.

The last experiment compared how well different age groups could legibly read increasingly smaller font sizes. The study compared Helvetica and Times New Roman as representative of the two main font families (serif and sans serif), which reflect part of the on-going debate as to which is preferable. Unlike the first two experiments, this study focused on age, cataract cloudiness, and visual acuity as possible influences on the legibility of characters on an e-paper device. All three factors had some degree of influence on the legibility of the two fonts read from the e-paper. However, visual acuity played a greater role as it had a negative correlation with both the smaller sizes for both fonts. However, more study is needed in order to deal with the respective height differences between fonts.

In total, this dissertation presents the results from three experiments that attempted to address the three fundamental concerns in ergonomics with regard to human interaction with Visual Display Terminals. The general concerns are with how environmental conditions, machine performance, and the human factor affect the legibility and readability of electronic devices. The three experiments analyzed and tested the effects of ambient illuminance, font sizes, and visual acuity. The purpose of the dissertation was to contribute to the recommendations of global standardization for the operation of electronic devices, particularly for elderly users.

Appendix: Dissertation Publications

These chapters are based on the following articles:

Chapter 2

R. P. Lege, S. Hasegawa, H. Ishio, T. Takahashi, K. Hyodo, S. Matsunami, Y. Ishii, K. Iwata, T. Kojima and M. Miyao, "Measuring the effects on lighting on the readability of electronic devices," Journal of the Society for Information Display (JSID), 2017 (in press).

Chapter 3

R. P. Lege, S. Matsunami, T. Kojima and M. Miyao, "How well the elderly evaluate the readability of E-papers--The effects of font sizes," Bulletin of Social Medicine, vol. 34, no. 1, 2017 (in press).

R. P. Lege, S. Matsunami, T. Kojima and M. Miyao, "How well the elderly evaluate the readability of E-paper devices: Standardization of minimum legible character size," Bulletin of Social Medicine, vol. 34, no. 1, 2017 (in press).

Chapter 4

R. P. Lege, N. Ishio, I. Morita, T. Kojima, R. Kimura, K. Iwata, S. Matsunami, H. Ishio and M. Miyao, "Effects of aging and visual acuity on the legible point size for a single character on E-paper display," Bulletin of Social Medicine, vol. 34, no. 2, 2017 (in press).

Works Cited

[1] K. Tomioka, "Study on the legibility of character for the elderly: Effects of character display modes on legibility," *Journal of physiological Anthropology,* vol. 26, pp. 159-164, 2007.

[2] A. Wang, C. Tseng, S. Jeng and K. Huang, "Effects of electronic-book display and inclination on users' comprehension under various ambient illuminance conditions," *Journal of the Society for Information Display,* vol. 16, no. 1, pp. 101-106, 2008.

[3] K. K. Shieh and D. S. Lee, "Preferred viewing distance and screen angle of electronic paper displays," *Applied Ergonomics,* vol. 38, pp. 601-607, 2007.

[4] E. Yamazaki, "History of CRT development," *Proceedings of the International Display Workshops: 14th Information Display Worshops,* pp. 729-732, 2007.

[5] H. Kawamoto, "The History of Liquid-Crstal Displays," *Proceedings of the Institute of Electrical Engineering,* vol. 90, pp. 460-500, 2002.

[6] W. Kim and Y. Koga, "Effect of local background luminance on discomfort glare," *Building and Environment,* vol. 39, pp. 1435-1442, 2004.

[7] S. Yang, J. Heikenfeld, E. Kreit, M. Hagdon, K. Dean, K. Zhou, S. Smith and J. Randolph, "Electrofluidic displays: Fundamental platforms and unique performance attributes," *Journal of the Society for Information Display,* vol. 19, no. 9, pp. 608-613, 2011.

[8] M. Hagdon, S. Yang, A. Russell and J. Heikenfeld, "Bright e-paper by transport of ink through a white electrofluidic imaging film," *Nature Communications,* vol. 3, pp. 1-7, 2012.

[9] J. Heikenfeld, P. Drzaic, J.-S. Yeo and T. Koch, "A critical review of the present and future prospects for electronic paper," *Journal of the Society for Information*

Display, vol. 19, no. 2, pp. 129-153, 2011.

[10] K. Nishimura, M. Omodani and J. Imai, "Novel evaluation method for visibility of reflective electronic paper display by comparative examnination with Liquid Crystal Display," *Society for Information Display Symposium Digest,* vol. 39, pp. 1355-1358, 2008.

[11] F. Kretzschmar, D. Pleimling, J. Hosemann, S. Fussel, I. Bornkessel-Schlesewky and M. Schlesewky, "Subjective impressions do not mirror online reading effort: Concurrent EEG-Eyetracking evidence from reading of books and digital media," PLOS ONE, 2013. [Online]. Available: http://dx.doi.org/10.1371/journal.pone.0056178. [Accessed 28 July 2016].

[12] E. Sieganthaler, Y. Bochud, P. Bergamin and P. Wurtz, "Reading on LCD vs e-Ink displays-Effects on fatigue and visual strain," *Ophthalmic and Physiological Optics,* vol. 32, pp. 367-774, 2012.

[13] S. Benedetto, V. Drai-Zerbib, M. Pedrotti, G. Tissier and T. Baccino, "E-Readers and visual fatigue," PLOS ONE, 2013. [Online]. Available: http://dx.org./10.1371/journal.pone.0083676. [Accessed 24 July 2016].

[14] T. Koizuka, S. Sano, T. Kojima and M. Miyao, "Evaluating the effects of environmental illuminance on the readability of E-books," *Society for Information Display Symposium Digest of Technical Papers,* vol. 44, no. 1, pp. 571-573, 2013.

[15] A. Wang, S. Hwang, H. Kuo and S. Jeng, "Effects of ambient illuminance and electronic displays on users' performance for young and elderly users," *Journal of the Society for Information Display,* vol. 18, no. 9, pp. 629-634, 2010.

[16] M. Bernard, B. Lida, S. Riley, T. Hackler and K. Janzen, "A comparison of popular online fonts: Which size and type is best?," Software Usability Research Laboratory, Wichita State University, 2002. [Online]. Available: http://usabilitynews.org/a-comparison-of-popular-online-fonts. [Accessed 3 12 2016].

[17] R. W. De Lange, H. L. Esterhuizen and D. Beatty, "Performance differences between

Times New Roman and Helvetica in a reading task," *Electronic Publishing,* vol. 6, no. 3, pp. 241-248, 1993.

[18] R. Sasson, Computers and Typography, Oxford: Intellect Books, 1993.

[19] M. Bernard, C. Liao and M. Mills, "Determining the best online font for older adults," Usability News, 2001. [Online]. Available: http://psychology.wichita.edu/surl/usabilitynews. [Accessed 13 12 2016].

[20] R. A. Morris, K. Aquilante, D. Yager and C. Bigelow, "Seriffs slow RSVP reading at very small sizes, but don't matter at larger sizes," *Society for Information Display International Symposium Digest of Technical Papers,* vol. 33, pp. 1-4, 2002.

[21] S. Walker and L. Reynolds, "Screen designs for children's reading," *Journal of research in Reading,* vol. 23, no. 2, pp. 224-234, 2000.

[22] E. Russell-Minda, J. W. Jutai, J. G. Strong, K. A. Campbell, D. Gold, L. Pretty and L. Wilmot, "Typeface legibility for readers with low vision: A research review," *Journal of Visual Impairments and Blindness,* vol. 101, pp. 402-415, 2007.

[23] W. Dick, D. Gadbury and A. Monge, "Adjusting typographic metrics to improve reading for people with low vision and other print disabilities," *Journal on Technology and Persons with Disabilities,* pp. 36-45, 2014.

[24] Japan Industrial Standard, "Ergonomics--office work with visual display terminals (VDTs)--visual display requirements," *JIS Z 8513,* pp. 1-29, 2006.

[25] A. Dillon, "Reading from paper versus screens a critical review of the emperical literature," *Ergonomics,* vol. 35, no. 10, pp. 1297-1326, 1992.

[26] J. M. Noyes and K. J. garland, "VDT versus paper-based reading: reply to Mayes, SIms, and Koonce," *International Journal of Industrial Ergonomics,* vol. 31, pp. 411-423, 2003.

[27] B. K. Hawes, T. Brunye, C. M. Mahoney, M. Sullivan and D. A. C, "Effect of four workplace lighting technologies on perception, cognition, and affective state," *International Journal of Industrial Ergonomics,* vol. 42, pp. 122-128, 2012.

[28] The Saif Corporation, "Industrial Hygiene: Lighting for office and industry," 2011. [Online]. Available: http://www.saif.com/_safetyhealthguides/ss-405.pdf. [Accessed 30 Sept 2016].

[29] M. E. Becker, "Recent advances in standardization of display metrology and light measurement," *Society for Information Display Digest,* pp. 716-719, 2015.

[30] T. Koizuka, Y. Ishii, T. Kojima, R. P. Lege and M. Miyao, "The contributions of built-in light on the readability in e-paper devices," *Society for Infroamtion Display Symposium Digest,* vol. 45, no. 1, pp. 861-864, 2014.

[31] T. Takahashi, "A review of electronic paper display technologies from the standpoint of SID Symposium Digests," The FPD Ergonomics Symposium, 2010. [Online]. Available: http://home.jeita.or.jp/device/lirec/symposium/fpd_2010/doc. [Accessed 24 July 2016].

[32] F. Funke, "Why semantical differentials in web-based research should be made from visual analogue scales and from 5-point scales," *Field Methods,* vol. 24, pp. 310-327, 2012.

[33] T. Koizuka, Y. Ishii, T. Kojima, N. Ishio, R. P. Lege and M. Miyao, "Proposing a baseline setup for readability," *Proceedings of the International Display Workshops,* pp. 1204-1205, 2014.

[34] ISO 9241-304, "User Performance test methods for electronic visual displays," International Organization for Standardization, 2008.

[35] H. Zervos, "E-readers: market propects and technology developments," Printed Electronic World, 2011. [Online]. Available: http://www.printedelectronicsworld.com. [Accessed 11 August 2016].

[36] M. Fritzpatrick, "Why Japanese readers don't ebooks," Fortune, 11 2 2013. [Online]. Available: http://fortune.com/2013/02/11. [Accessed 24 July 2016].

[37] W. Ballhaus, "Turning the page: The future of ebooks," Technology, Media & Telecommunications, 2015. [Online]. Available: http://www.pwc.co.uk/assets/pdf. [Accessed 10 August 2016].

[38] A. H. Wang, S. L. Hwang, H. T. Kuo and S. C. Jeng, "Effects of ambient illuminance and electronic displays on users' visual performance for young and elderly users," *Journal of the Society for Information Display,* vol. 18, no. 9, pp. 629-634, 2010.

[39] I. H. Shen, K. K. Shieh, C. Y. Chao and D. S. Lee, "Lighting, font style, and polarity on visual performance and visual fatigue with electronic paper displays," *Displays,* vol. 30, pp. 53-58, 2008.

[40] A. H. Wang, H. T. Kuo and S. C. Jeng, "Effects of ambient illuminance on users' visual performance using various electronic displays," *Journal of the Society for Information Display,* vol. 17, pp. 665-669, 2009.

[41] S. Sano, T. Kanda, K. Uemoto, A. Hasegawa, T. Kojima and M. Miyao, "The effects of illuminance on visibility of reading tablet devices and E-paper," *Society for Information Display,* pp. 1186-1189, 2012.

[42] P. C. Chang, S. Y. Chou and K. K. Shieh, "Reading perfromance and visual fatigue when using electronic paper displays in long-duation reading tasks under various lighting conditions," *Displays,* vol. 34, pp. 208-214, 2013.

[43] Amazon, "Amazon.com Kindle DX," Amazon, n.d.. [Online]. Available: https://www.amazon.com/Kindle-DX-wireless-reader-3G-Global/dp/B002GYWHSQ. [Accessed 11 November 2016].

[44] Apple, "Apple-iPad," Apple, n.d.. [Online]. Available: https://support.apple.com/kb/SP647. [Accessed 11 November 2016].

[45] S. Ueki, T. Taguchi, K. Nakamura, Y. Itoh and K. Okamoto, "New metrics based on visual perception for evaluating image quality," *Proceedings of the Internationla Displays Workshops,* vol. 1, pp. 519-522, 2006.

[46] ISO 8995, "Lighting of indoor work places," *International Organization for Standardization,* 2002.

[47] ISO 9241-304, "User performance test methods for electronic visual displays," *International Organization for Standardization,* 2008.

[48] R. Stroud, "Courier fonts: Everything you wnated to know about courier fonts," n.d.. [Online]. Available: http://www.rolandstroud.com/downloads/essays/courierfonts/pdf. [Accessed 2 October 2016].

[49] L. Tarita-Nistor, D. Lam, M. H. Brent, M. J. Steinbach and E. G. Gonzalez, "Courier: a better font for reading with age-related macular degeneration," *Canadian Ophthamological Society,* vol. 48, pp. 56-62, 2013.

[50] S. Matsunami, T. Koizuka, R. P. Lege, T. Kojima and M. Miyao, "The effects of ambient illuminance and aging on the evaluation of the readability of E-paper," *Journal of the Institute of Image Information and Television Engineers,* vol. 69, no. 10, pp. 306-313, 2015.

[51] D. Lee, Y. Ko, I. Shen and C. Chao, "Effect of light source, ambient illumination, character size and interline spacing on visual performance and visual fatigue with electronic paper displays," *Displays,* vol. 32, pp. 1-7, 2011.

[52] Y. Takubo, Y. Hisatake, T. Iizuka and T. Kawamura, "Ultra-high resolution mobile displays," *Society for Infromation Display Symposium Digest,* vol. 43, no. 1, pp. 869-872, 2012.

[53] Y. Ishii, T. Koizuka, R. Cui, T. Kojima and M. Miyao, "Evlauation of readability for tablet devices by the severity of cataract cloudiness," *Society for Information Dislpay Symposium Digest,* vol. 45, no. 1, pp. 1089-1092, 2014.

[54] A. Dillion, "Reading from paper versus screens: a critical review of the emperical literature," *Ergonomics,* vol. 35, no. 10, pp. 1297-1326, 1992.

[55] International Council of Ophthalmology, "Visual acuity measurement standard-ICO," 1984. [Online]. Available: http://www.icoph.org/dynamic/attachments/resources/icovisualacuity1984.pdf. [Accessed 29 December 2016].

[56] K. Kerber, G. P. Ishiyama and R. W. Baloh, "A longtiudnal study of oculomotor function in normal older people," *Neurobiology of Aging,* vol. 27, pp. 1346-1353, 2006.

[57] K. Rayner, E. D. Reichle, M. Stroud, C. Williams and A. Pollatsek, "The effect of word frequency, word predictability, and font difficulty on the eye movements of young and older readers," *Psychology and Aging,* vol. 21, pp. 448-465, 2006.

[58] C. Owsley, "Aging and vision," *Vision Research,* vol. 51, pp. 1610-1622, 2011.

[59] Pricewaterhousecoopers, "Global Entertainment and Media Outlook," PWC, 2014. [Online]. [Accessed 9 September 2016].

[60] TechNavio, "Global E-book market 2015-2019," Infiniti Research Ltd., 2014. [Online]. Available: www.technavio.com/report/global-e-book-market-2015-2019. [Accessed 10 September 2016].

[61] N. Collins, "The Telegraph: Electronic readers "better than books" for older people," 6 February 2013. [Online]. Available: http://www.telegraph.co.uk/news/science/science-news/9852996. [Accessed 22 September 2016].

[62] R. A. Weale, "Senile changes in visual acuity," *Transactions of the Ophthalmological Societies of the United Kingdom,* vol. 95, no. 1, pp. 36-38, 1979.

[63] F. S. Said and R. A. Weale, "The variation with age of the spectral transmissivity of the living human cyrstalline lens," *Gerontologia,* vol. 3, pp. 213-231, 1959.

[64] K. Sasaki and T. Yamamura, "current cataract epidemiology studies in Japan," *Developments in Ophthalmology,* vol. 21, pp. 18-22, 1991.

[65] K. Sagawa and Y. Takahashi, "Spectral luminous efficiency as a function of age," *Journal of the Optical Society of America,* vol. A18, pp. 2659-2667, 2001.

[66] Amazon, "Amazon Paperwhite," Amazon.com, n.d.. [Online]. Available: http://www.amazon.co.jp/dp/B00QJDQM9U. [Accessed 6 December 2016].

[67] Japan Industrial Standard, "General rules of recommended lighting levels," *JIS Z 9110,* 2011.

[68] D. B. Stone, S. K. Fisher and J. Eliot, "Adults' propr exporsure to print as a predicator of legibility of text on paper and laptop computer," *Reading and Writing: Interdisciplinary Journal,* vol. 11, pp. 1-28, 1999.

[69] Japan Industrial Standard, "Guidelines for the elderly and people with disabilities-Visual signs and displays-Estimation of minimum legible size for a Japanese single character," *JIS 0032,* 2013.

[70] K. Sagawa and K. Kurakata, "Estimeation of legible font sizes for elderly people: Accessible design of characterrs in signs and displays and its standardization," *Synthesiology,* vol. 6, no. 1, pp. 24-33, 2013.

[71] S. Sano, T. Kojima and M. Miyao, "The effect of illuminance on visibility during reading e-books by age groups," *Proceedings of the International Display Workshops,* vol. 12, pp. 691-694, 2012.

[72] D. Lee, K. K. Shieh, S. Jeng and I. Shen, "Effect of character size and lighting on the legibility of electronic papers," *Displays,* pp. 10-17, 2012.